

# The search for dark photons and the g-2 anomaly

Rouven Essig

Yang Institute for Theoretical Physics, Stony Brook

Joint Experimental-Theoretical Seminar  
&  
g-2 Collaboration Meeting

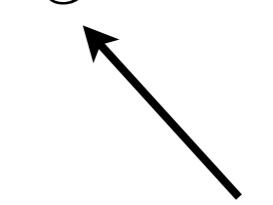
Fermilab, Jan. 13th, 2012

# Muon Anomalous Magnetic Moment

the subject of this week's  
g-2 Collaboration Meeting  
@ Fermilab ...

# Muon Anomalous Magnetic Moment

magnetic dipole moment  
of charged particle

$$\vec{\mu} = g_s \left( \frac{q}{2m} \right) \vec{s}$$


spin

# Muon Anomalous Magnetic Moment

magnetic dipole moment  
of charged particle

$$\vec{\mu} = g_s \left( \frac{q}{2m} \right) \vec{s}$$

spin

can be measured  
very accurately

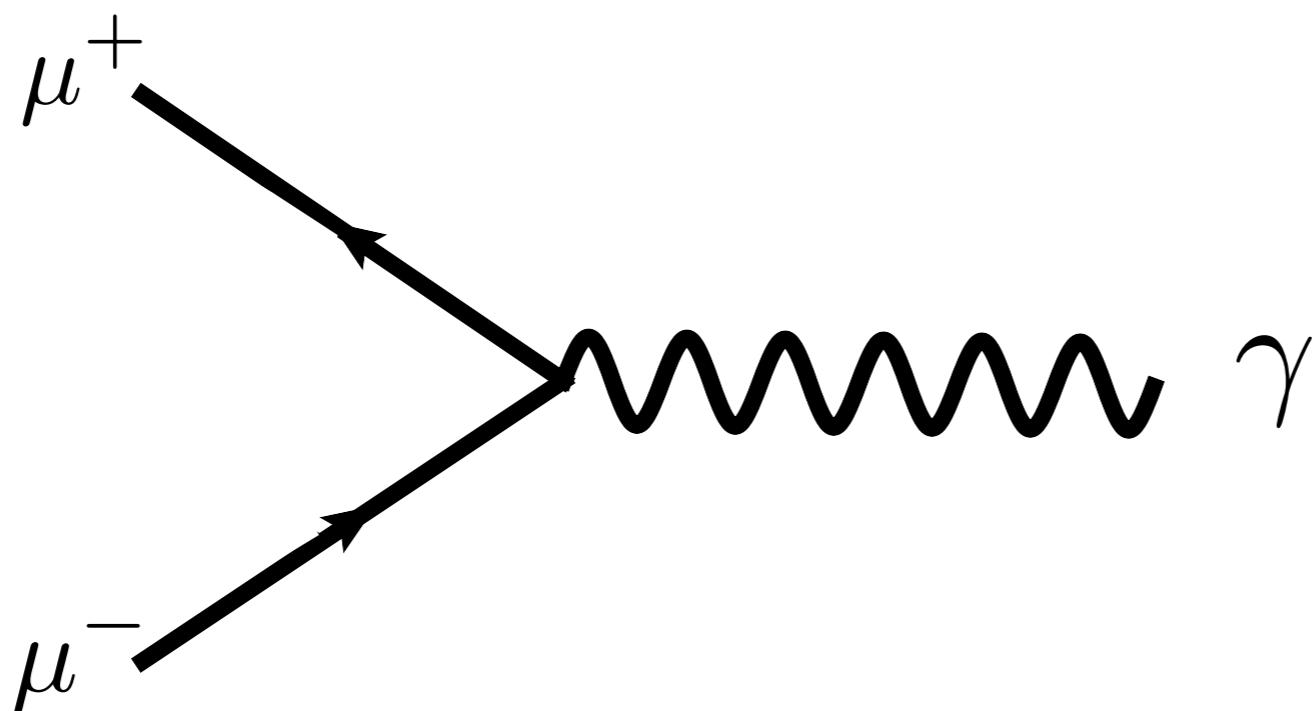
# Muon Anomalous Magnetic Moment

magnetic dipole moment  
of charged particle

$$\vec{\mu} = g_s \left( \frac{q}{2m} \right) \vec{s}$$

can be measured  
very accurately

spin



$$g_s = 2$$

(Dirac)

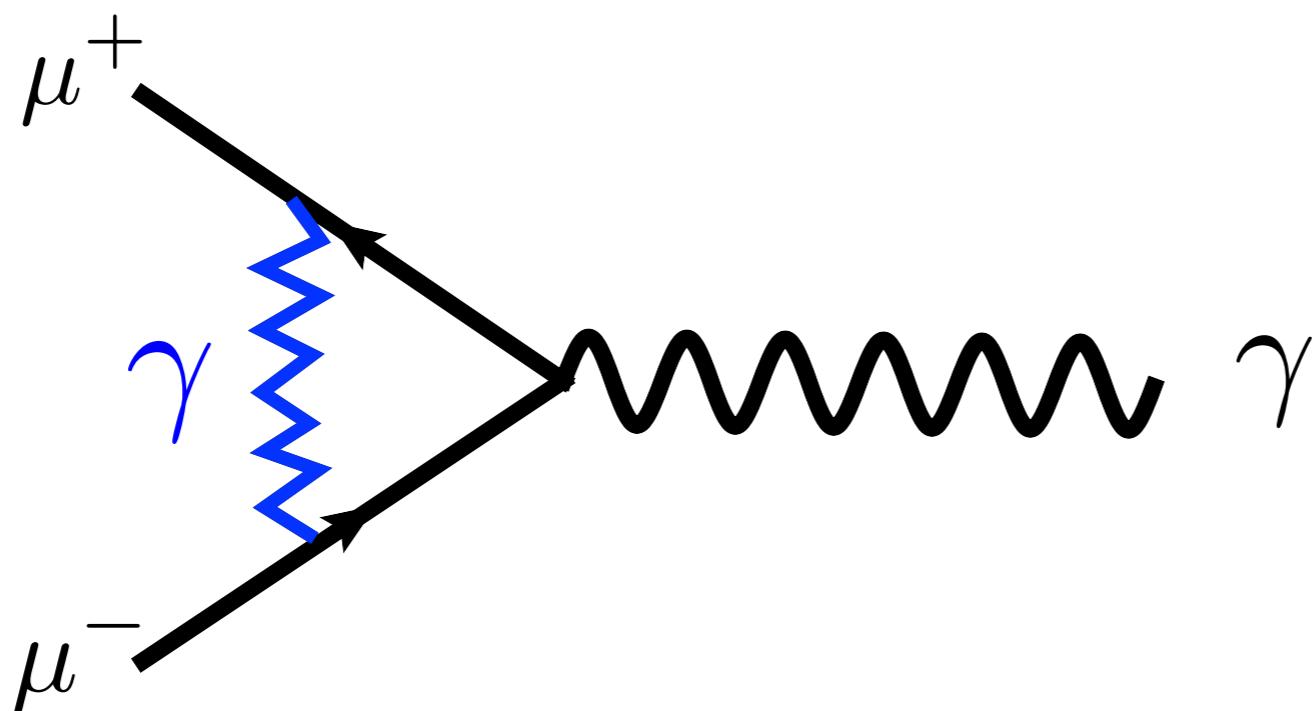
# Muon Anomalous Magnetic Moment

magnetic dipole moment  
of charged particle

$$\vec{\mu} = g_s \left( \frac{q}{2m} \right) \vec{s}$$

spin

can be measured  
very accurately



$$g_s \neq 2$$

(Standard Model)

“Anomalous” magnetic moment  $\sim g_s - 2$

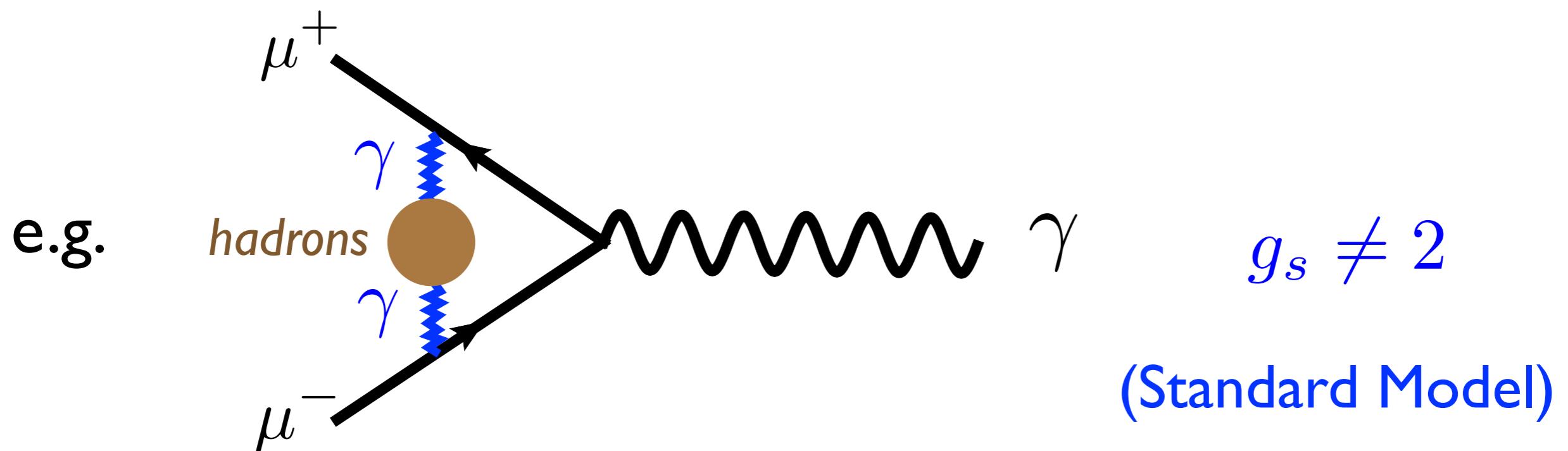
# Muon Anomalous Magnetic Moment

magnetic dipole moment  
of charged particle

$$\vec{\mu} = g_s \left( \frac{q}{2m} \right) \vec{s}$$

spin

can be measured  
very accurately



difficult to calculate precisely in Standard Model...

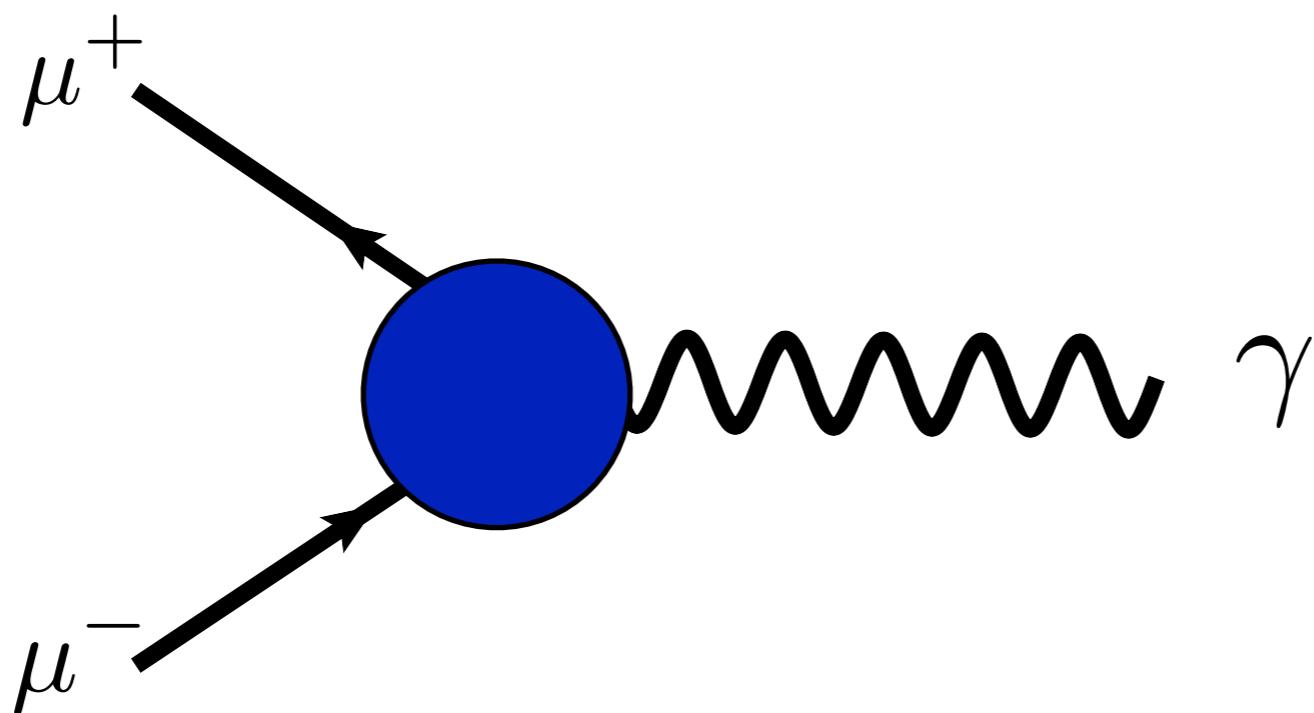
# Muon Anomalous Magnetic Moment

magnetic dipole moment  
of charged particle

$$\vec{\mu} = g_s \left( \frac{q}{2m} \right) \vec{s}$$

spin

can be measured  
very accurately



$$g_s \neq 2$$

(Standard Model)

Standard Model  
 $(g_s - 2)_\mu$  versus Data

$\sim 3.2 \sigma$  deviation

# Muon Anomalous Magnetic Moment

Standard Model  
 $(g_s - 2)_\mu$  versus Data

~ 3.2  $\sigma$  deviation

# Muon Anomalous Magnetic Moment

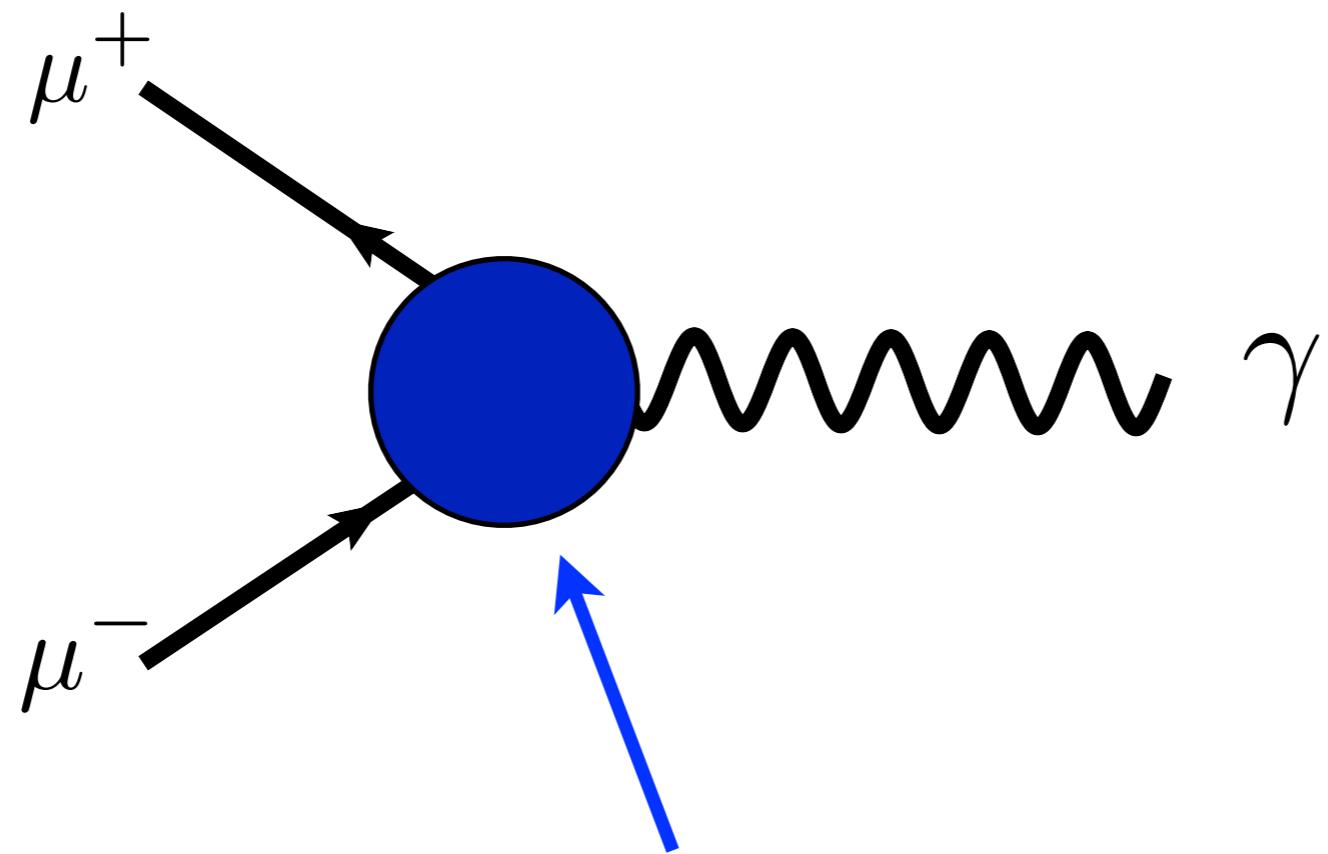
Standard Model  
 $(g_s - 2)_\mu$  versus Data       $\sim 3.2 \sigma$  deviation

## Evidence for New Physics?

# Muon Anomalous Magnetic Moment

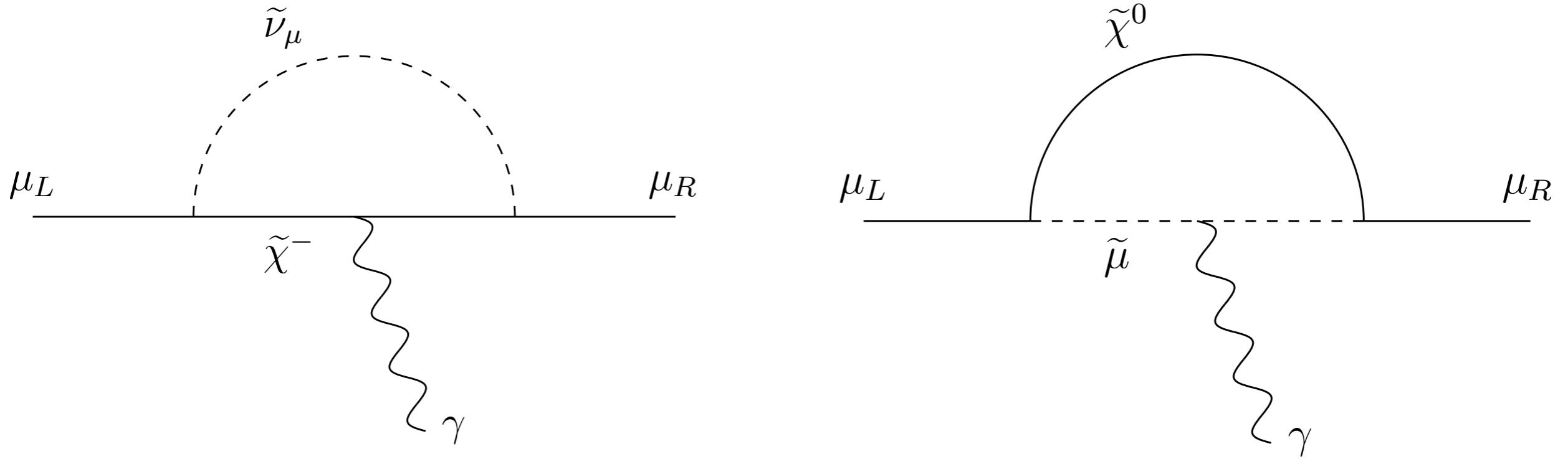
Standard Model  
 $(g_s - 2)_\mu$  versus Data       $\sim 3.2 \sigma$  deviation

## Evidence for New Physics?



Loops of new particles could explain it... many possibilities

# Example: supersymmetry



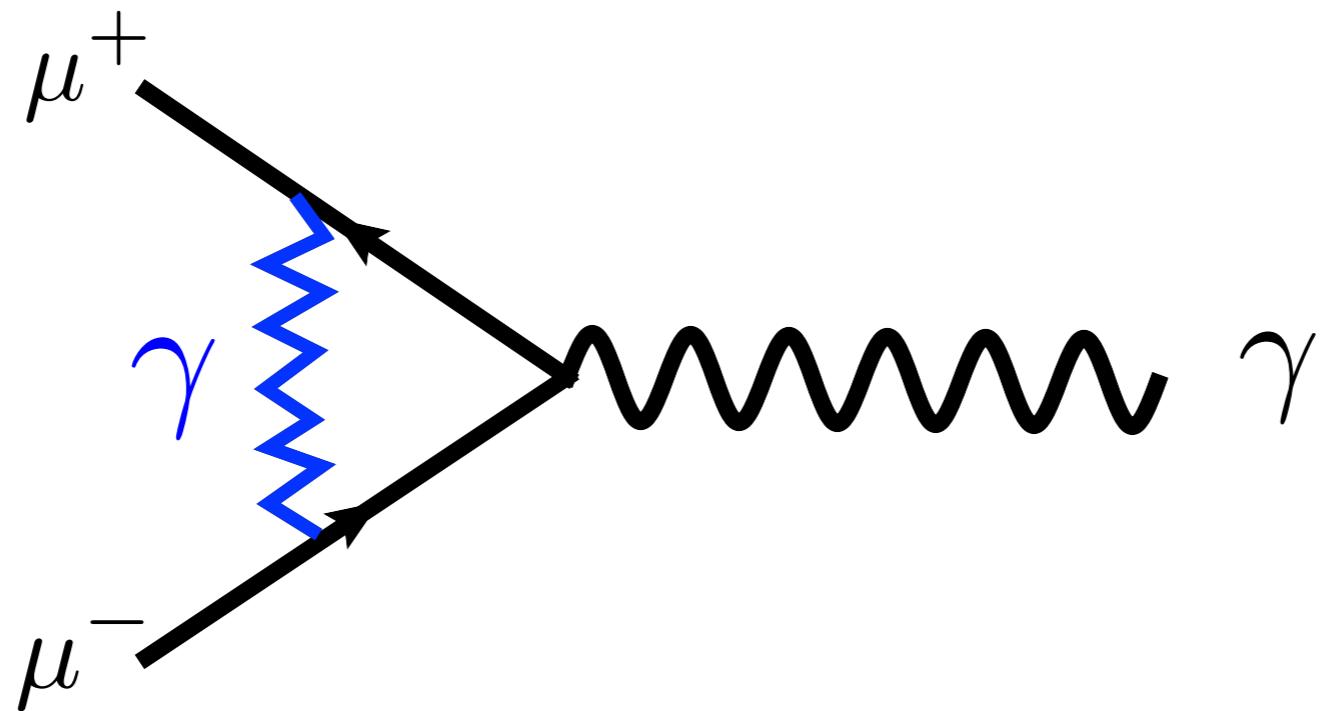
need light sleptons & charginos

depends on 7 parameters:

$\mu, m_{\tilde{\mu}_L}, m_{\tilde{\mu}_L}, M_1, M_2, \tan \beta, A_\mu$

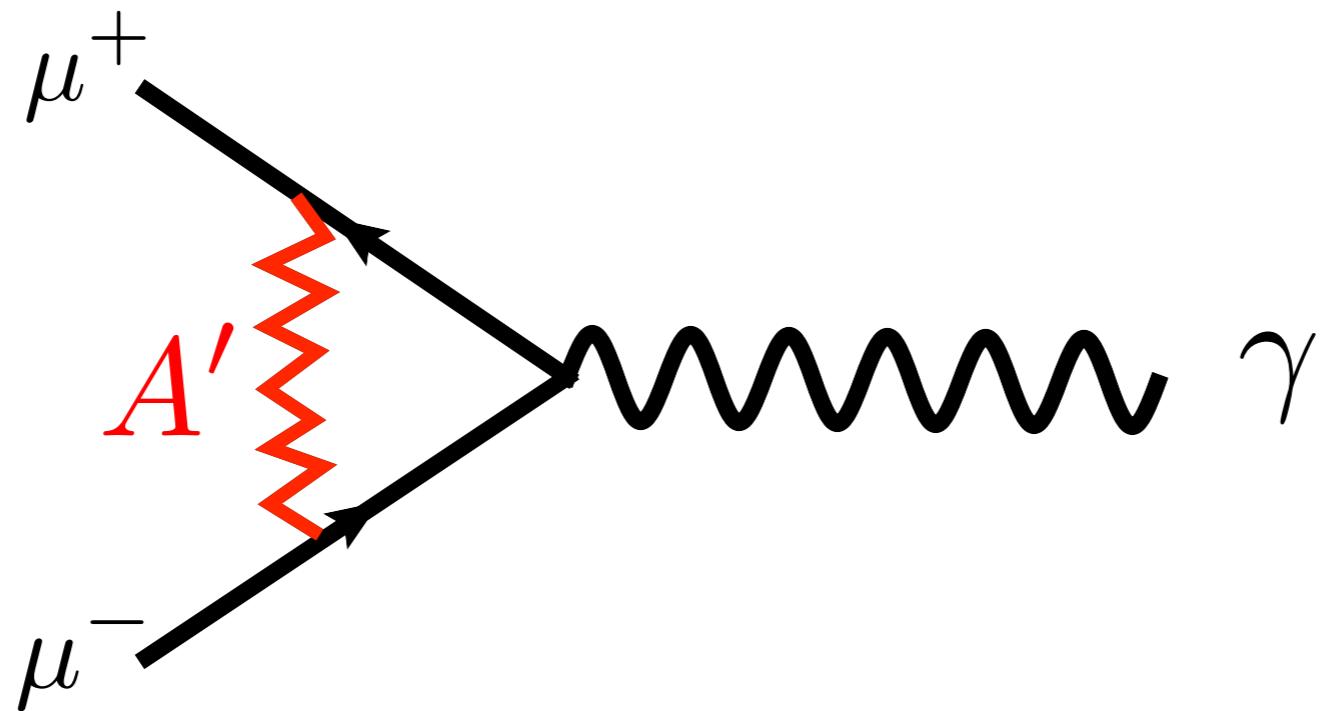
# This talk: a very simple possibility

# This talk: a very simple possibility



consider not a *photon*...

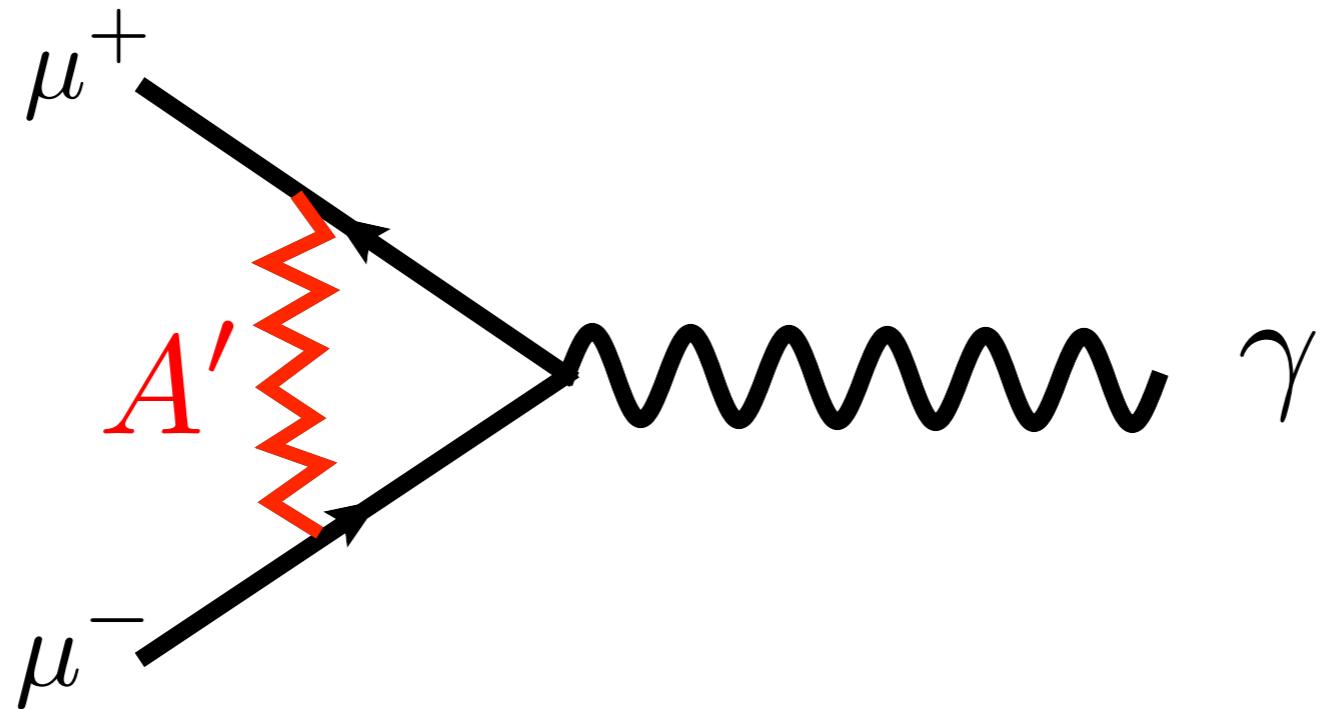
# This talk: a very simple possibility



consider not a *photon*...

but a “*massive*” or “*dark*” photon:  $A'$

# This talk: a very simple possibility

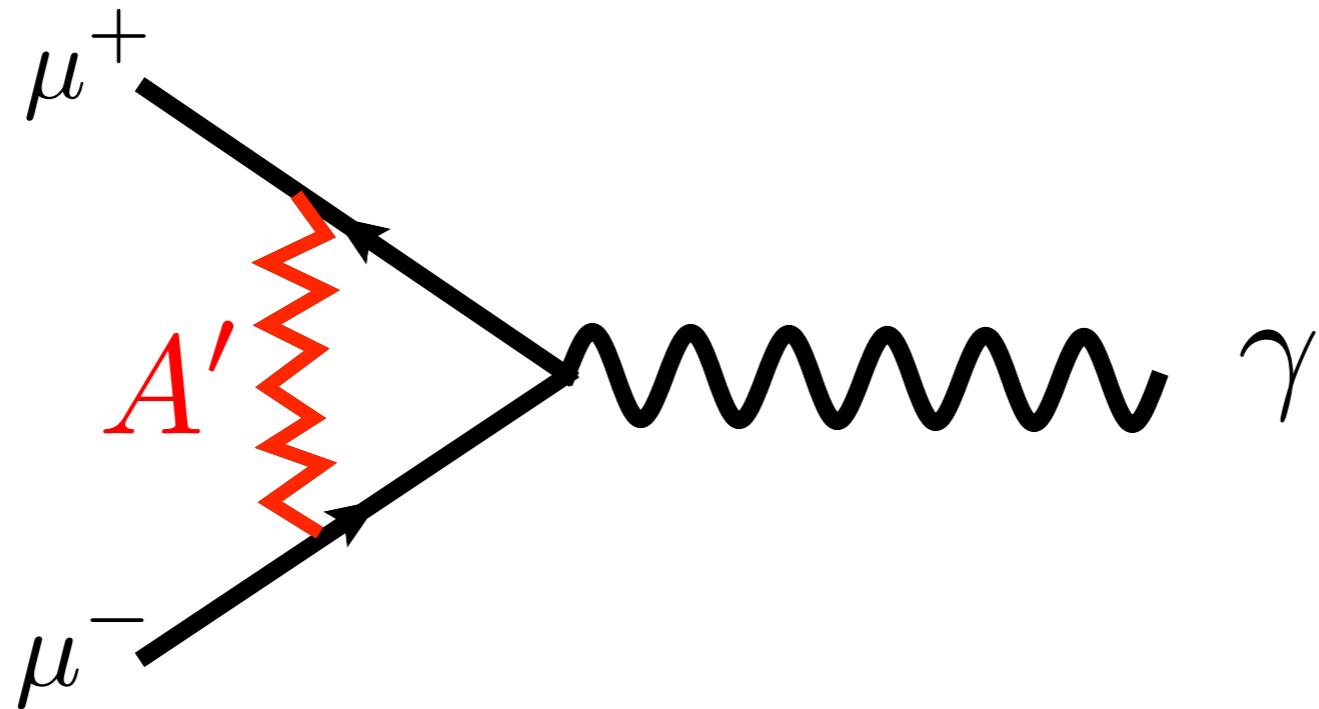


consider not a *photon*...

but a “*massive*” or “*dark*” photon:  $A'$

- mediates a new force

# This talk: a very simple possibility

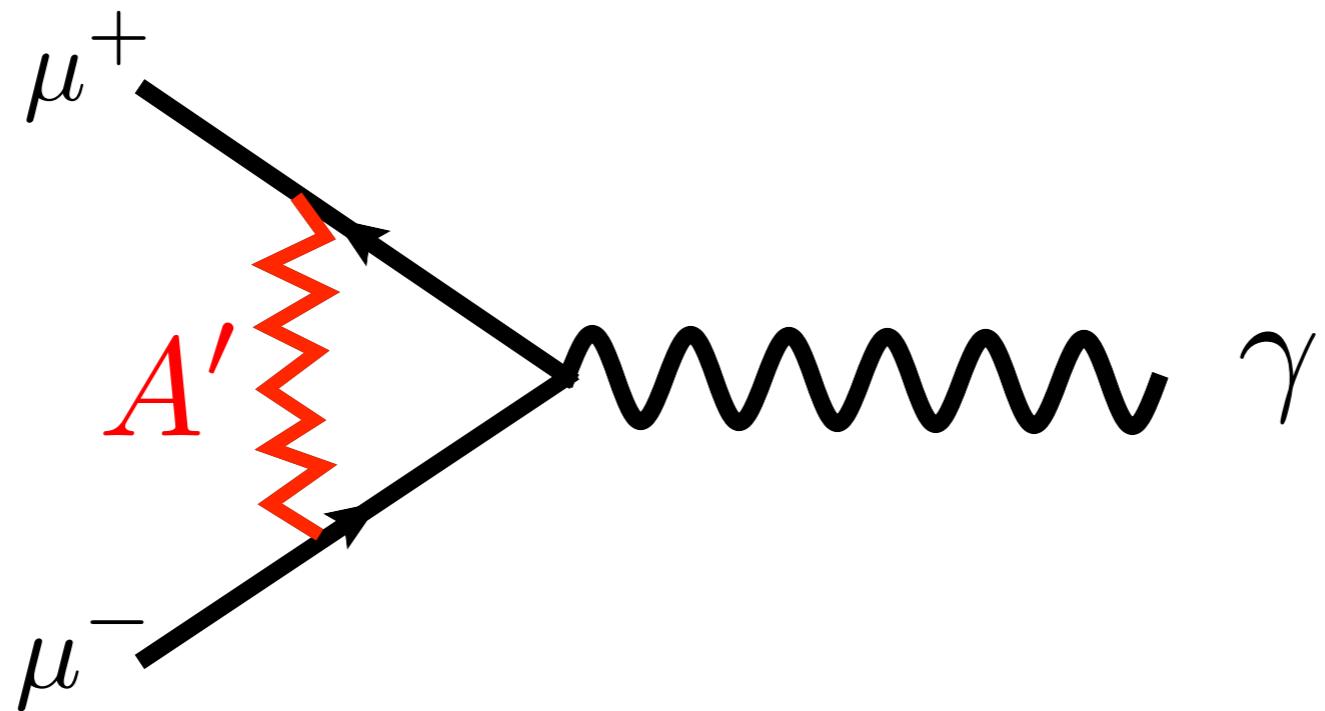


consider not a *photon*...

but a “*massive*” or “*dark*” photon:  $A'$

- mediates a **new force**
- weakly coupled to electrically charged matter

# This talk: a very simple possibility



consider not a *photon*...

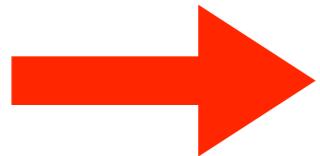
but a “*massive*” or “*dark*” photon:  $A'$

- mediates a **new force**
- weakly coupled to electrically charged matter
- focus on **mass** of  $A' \sim 1 \text{ MeV} - 1 \text{ GeV}$

# Outline

- Theory
- Motivation (“hints”)
- Searches
  - $e^+e^-$  colliders
  - fixed target:  $e^-$  and  $p$
  - Tevatron & LHC

# Outline



- Theory
- Motivation (“hints”)
- Searches
  - $e^+e^-$  colliders
  - fixed target:  $e^-$  and  $p$
  - Tevatron & LHC

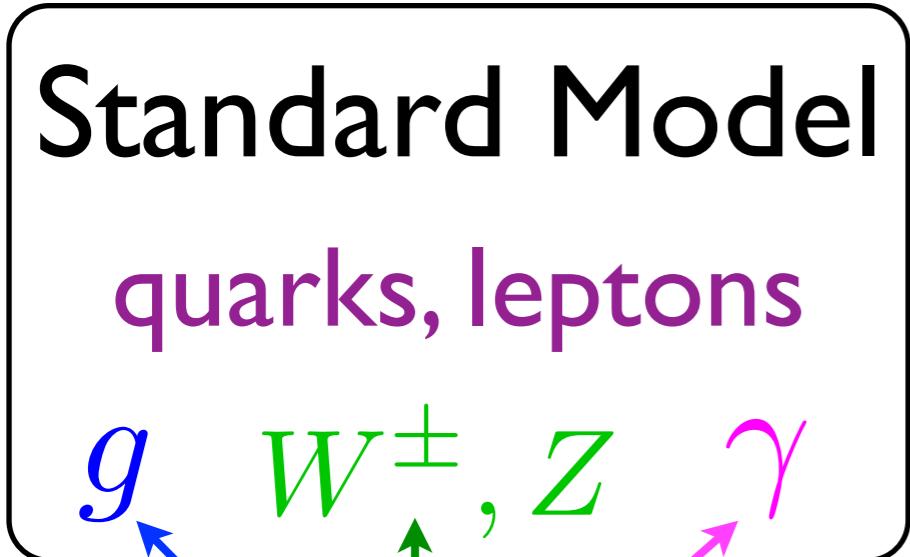
# A new force

Standard Model

quarks, leptons

$g$     $W^\pm, Z$     $\gamma$

# A new force

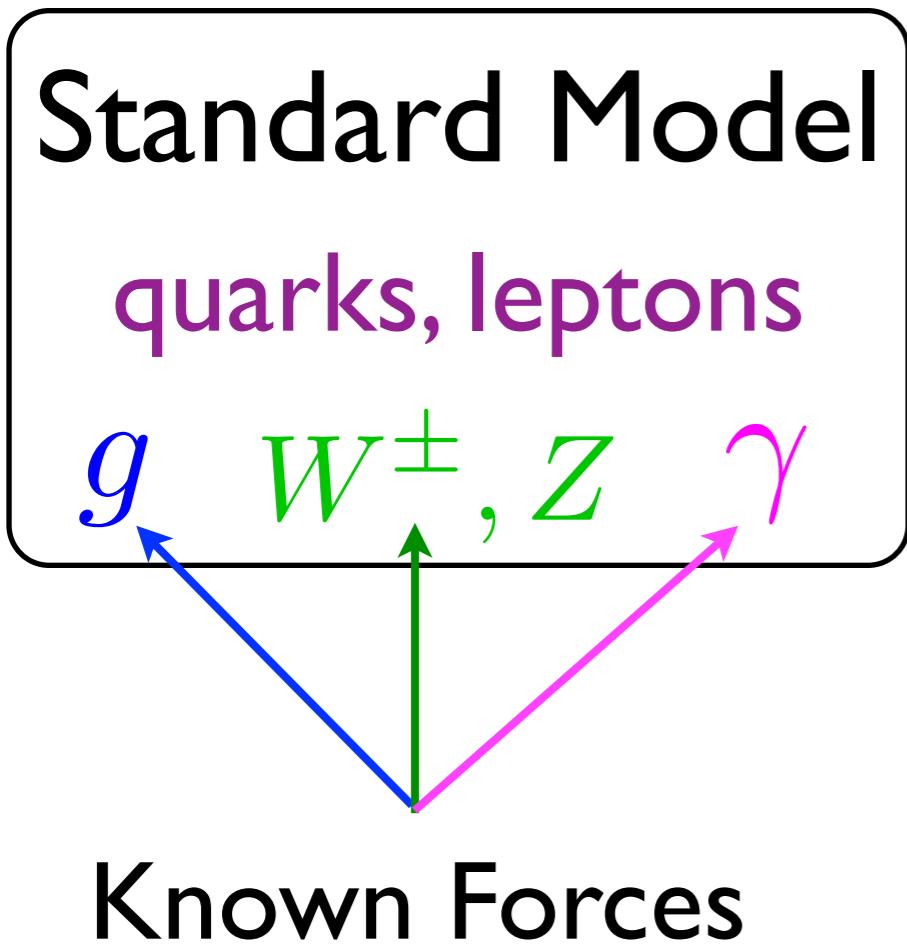


Known Forces

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

# A new force

A hidden sector, with particles that do  
not couple to known forces

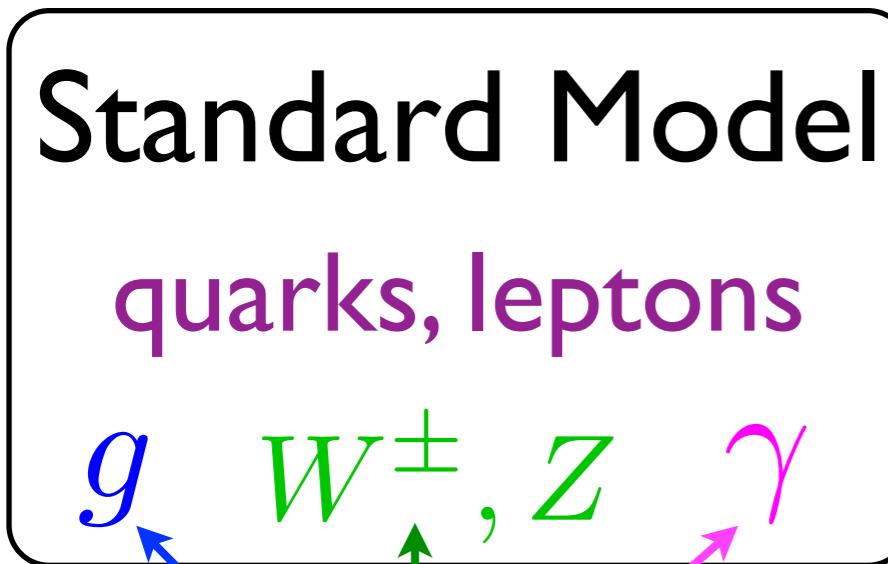


cf. “Hidden Valley” models  
Strassler et.al. [2006]

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

# A new force

A hidden sector, with particles that do  
not couple to known forces



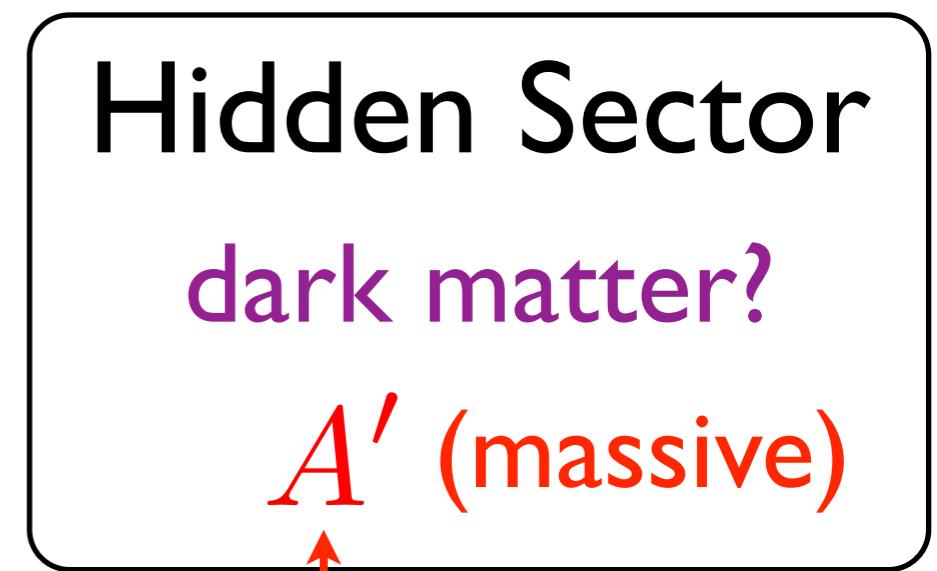
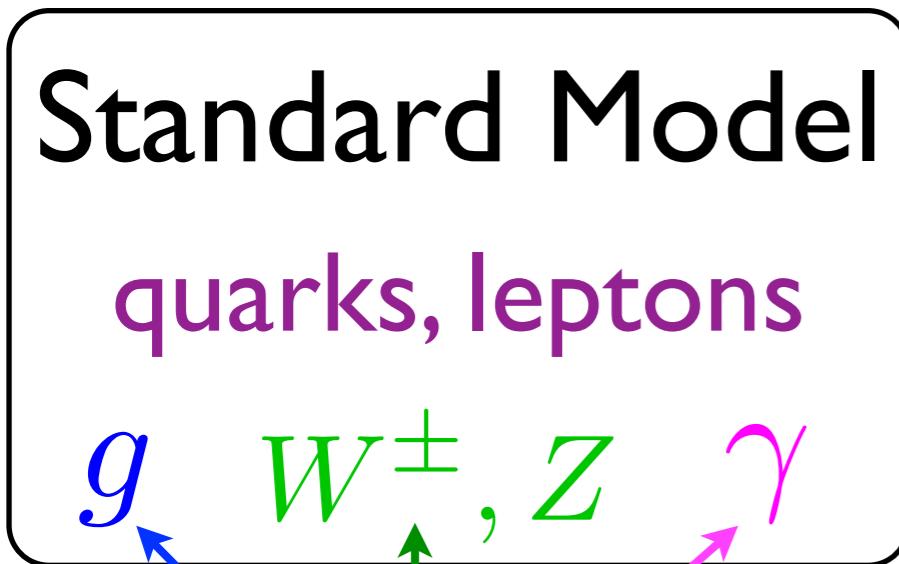
Known Forces

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Hidden Sector  
dark matter?

# A new force

A hidden sector, with particles that do not couple to known forces

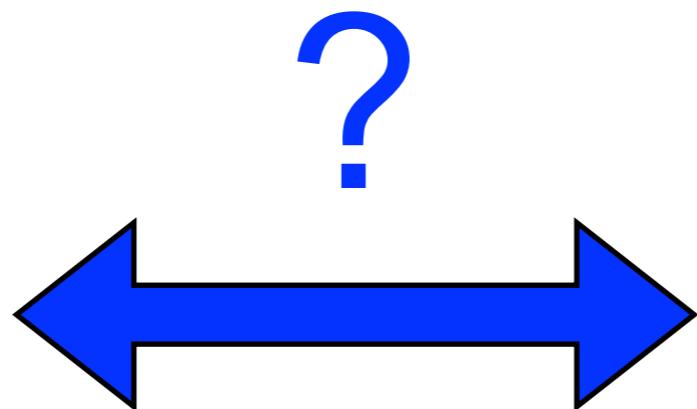


$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$U(1)'$$

# Coupling?

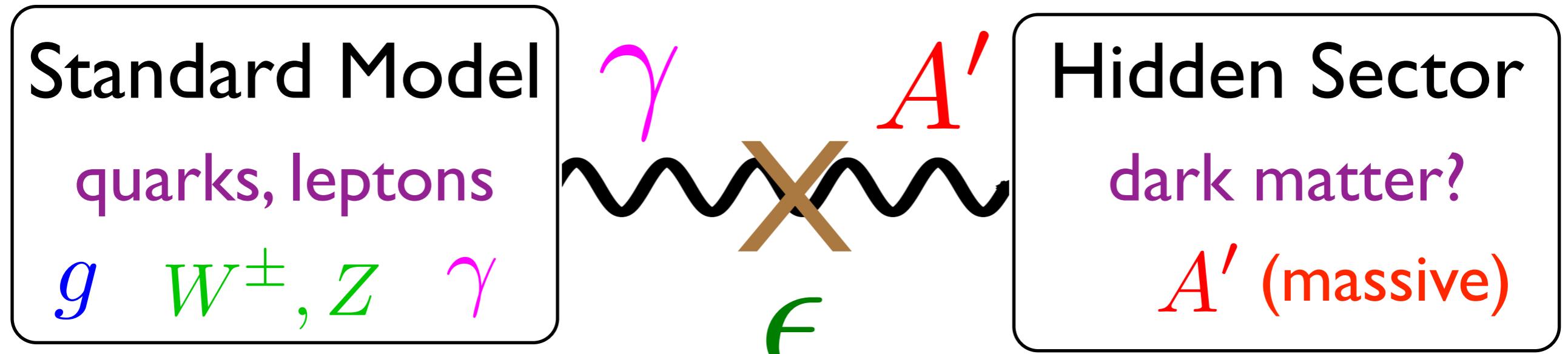
Standard Model  
quarks, leptons  
 $g$     $W^\pm, Z$     $\gamma$



Hidden Sector  
dark matter?  
 $A'$  (massive)

# The photon and $A'$ can mix !

Holdom  
Galison, Manohar



$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

“Kinetic Mixing”

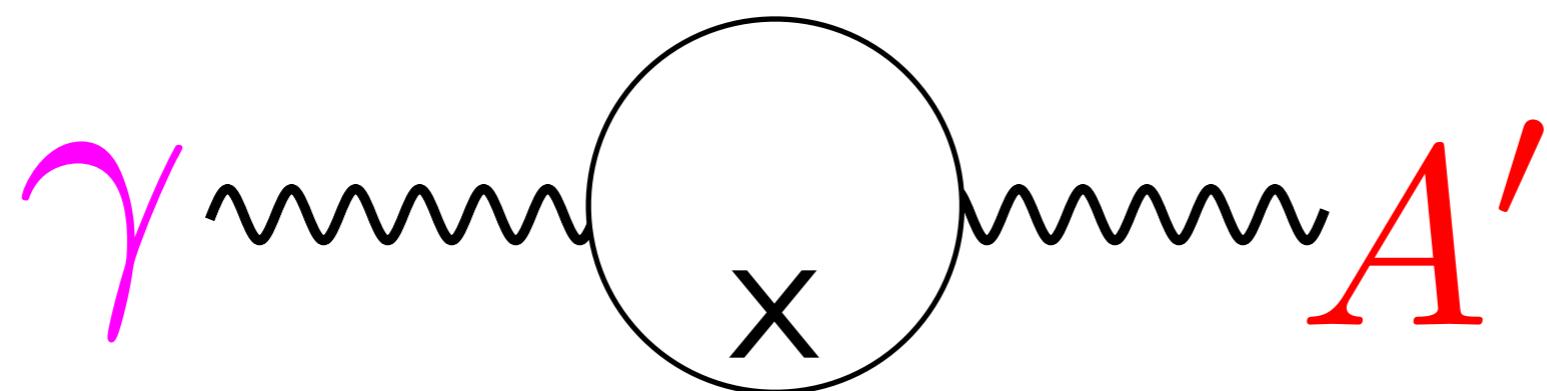


$\epsilon$  = mixing strength



$\epsilon = \text{mixing strength}$

Generated by heavy particles  
 $X$  interacting with  $\gamma$  and  $A'$



$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

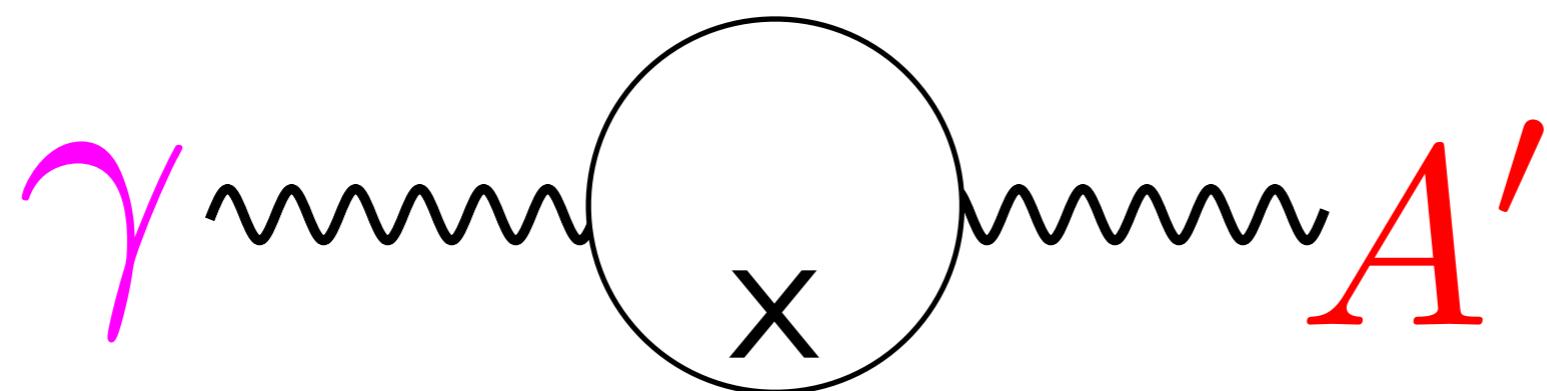
“Kinetic Mixing”

$\epsilon$  could even be  $O(1)$  (theoretically)



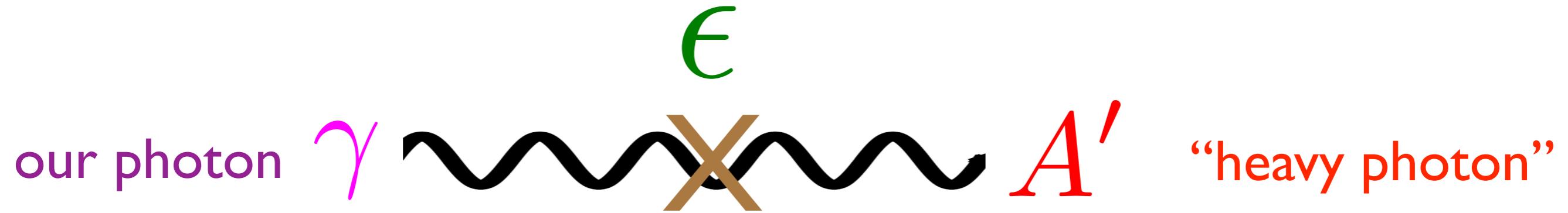
$\epsilon = \text{mixing strength}$

Generated by heavy particles  
X interacting with  $\gamma$  and  $A'$

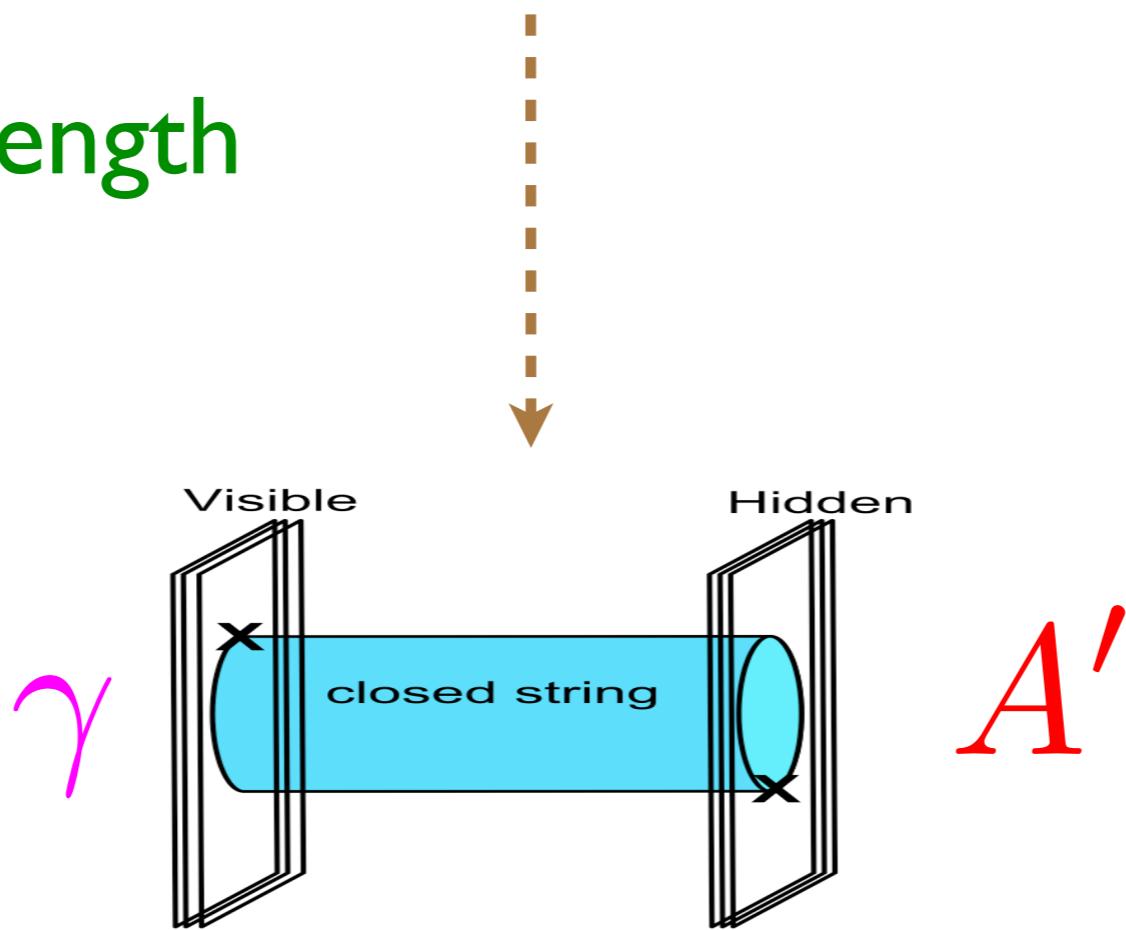


$$\epsilon \sim 10^{-8} - 10^{-2}$$

natural from  
loops of heavy particles

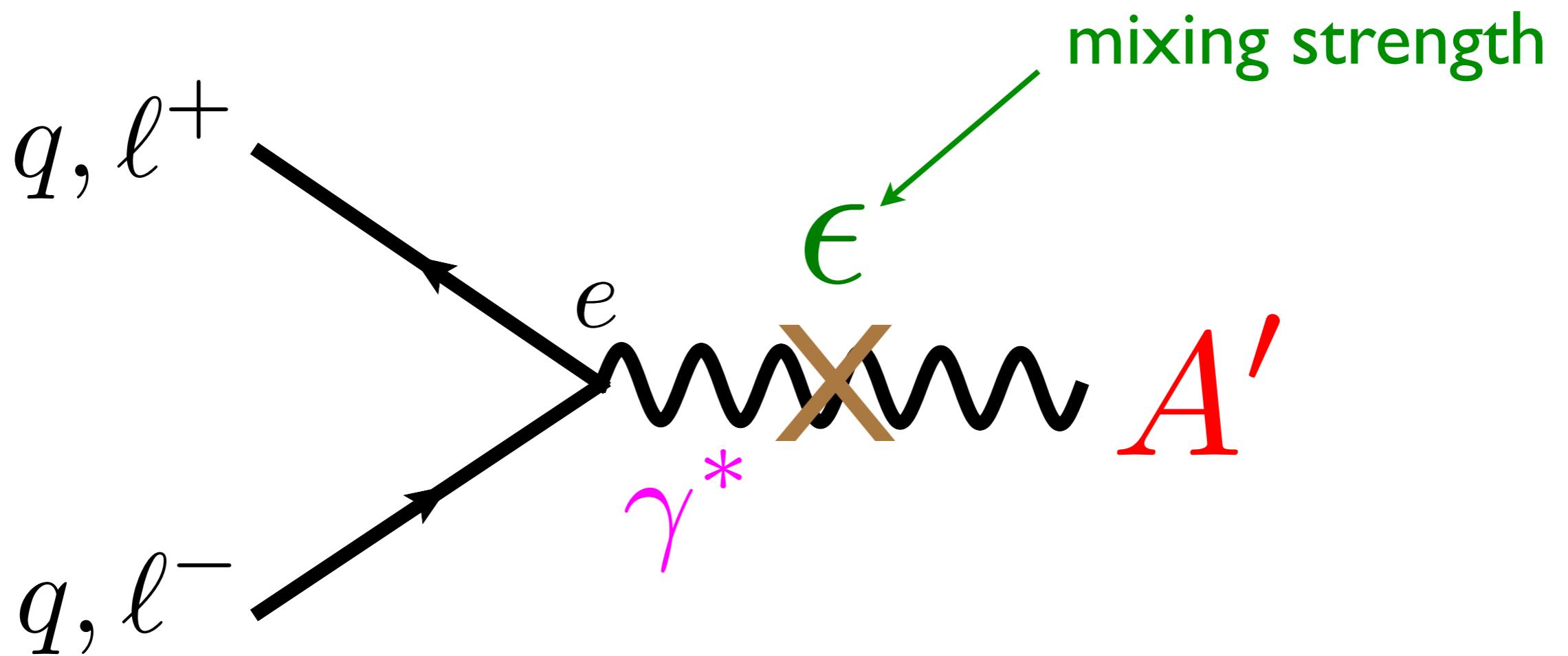


$\epsilon = \text{mixing strength}$

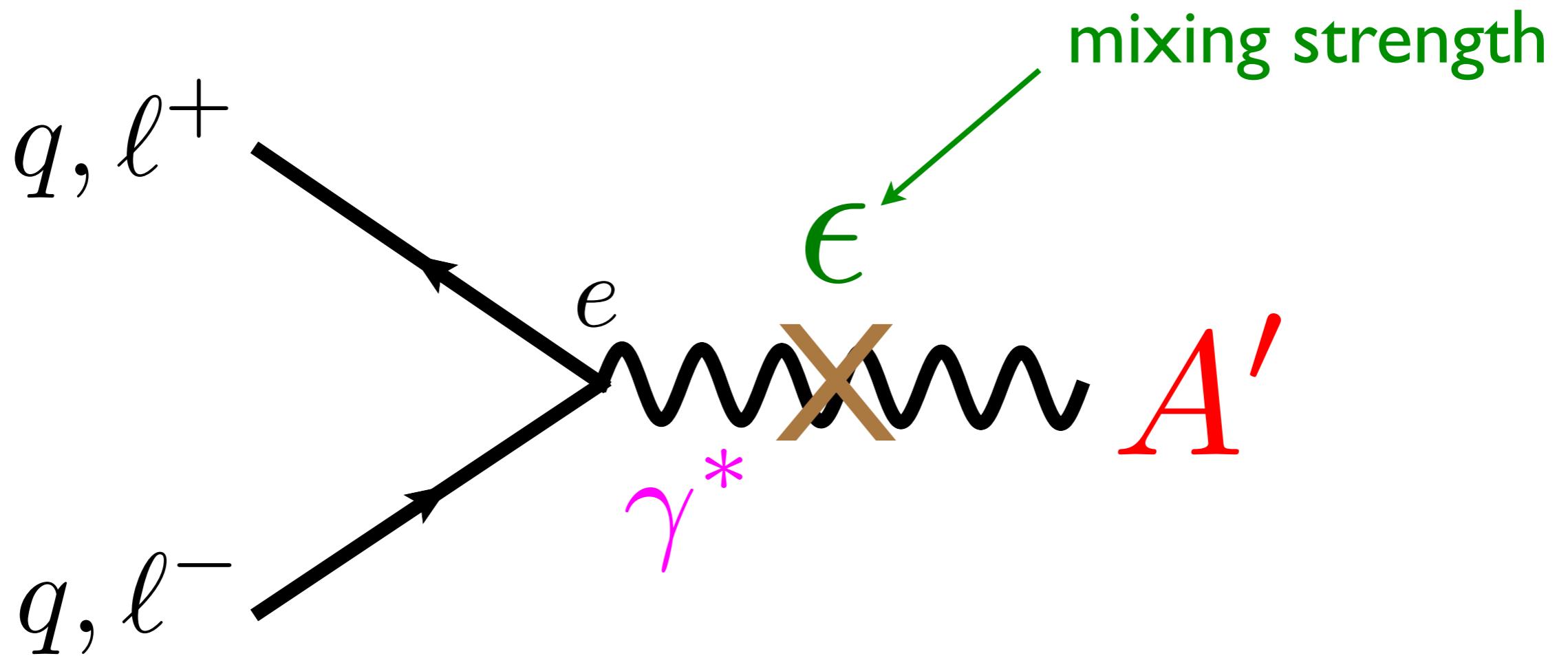


in string theory  $\epsilon \ll 1$  is also possible

# A' couples to Quarks and charged Leptons

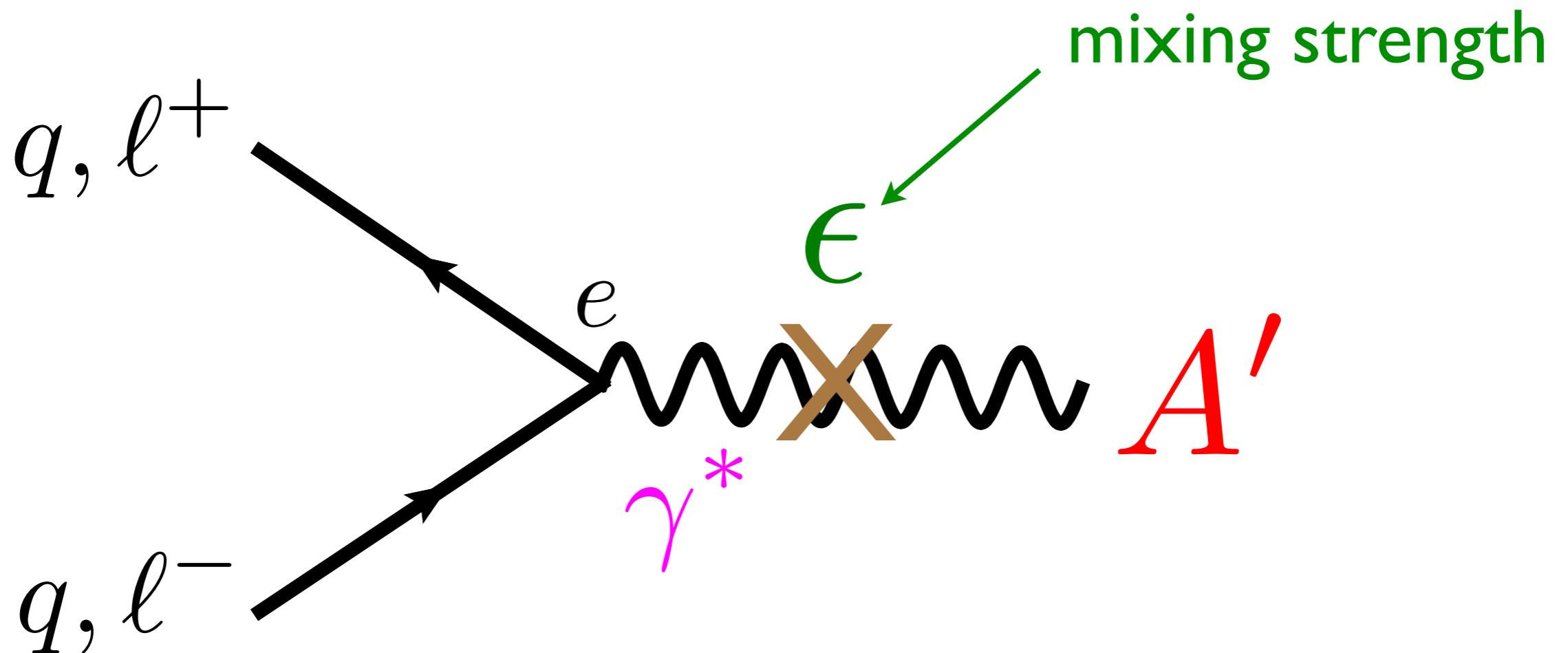


# $A'$ couples to Quarks and charged Leptons



focus on Mass of  $A' \sim 1 \text{ MeV} - 1 \text{ GeV}$   
(theoretically natural, motivated from data)

# A' couples to Quarks and charged Leptons



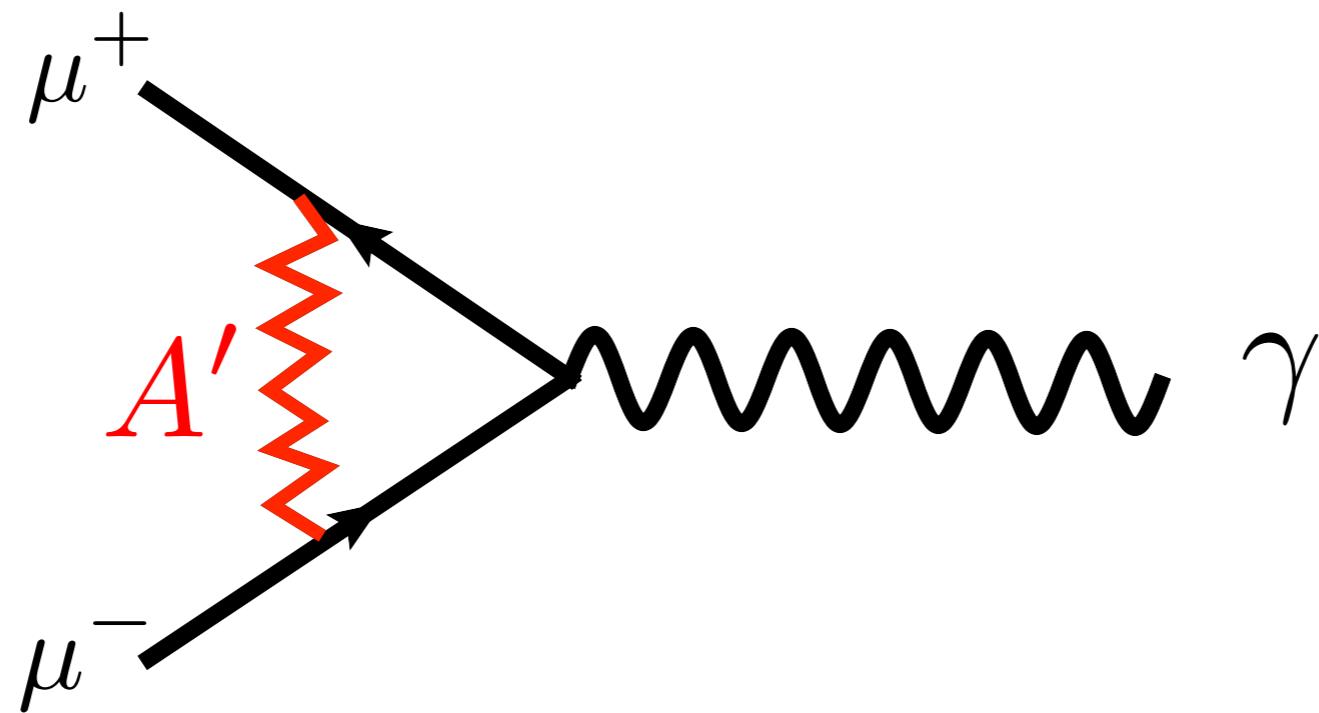
focus on Mass of  $A' \sim 1 \text{ MeV} - 1 \text{ GeV}$   
(theoretically natural, motivated from data)

Hints for  $A'?$

# Outline

- Theory
- • Motivation (“hints”)
- Searches
  - $e^+e^-$  colliders
  - fixed target:  $e^-$  and  $p$
  - Tevatron & LHC

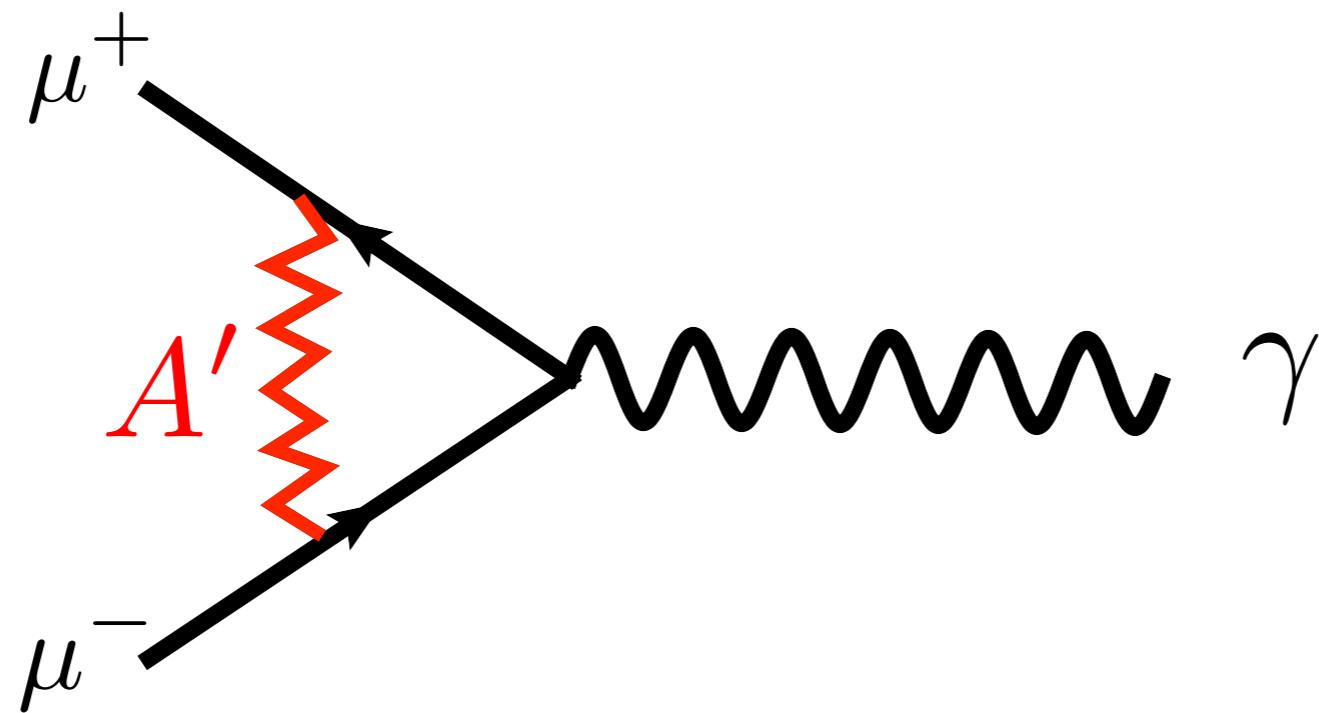
# Muon's anomalous magnetic moment?



Pospelov  
Boehm, Fayet

$A'$  may explain observed  $(g_s - 2)_\mu$ !

# Muon's anomalous magnetic moment?



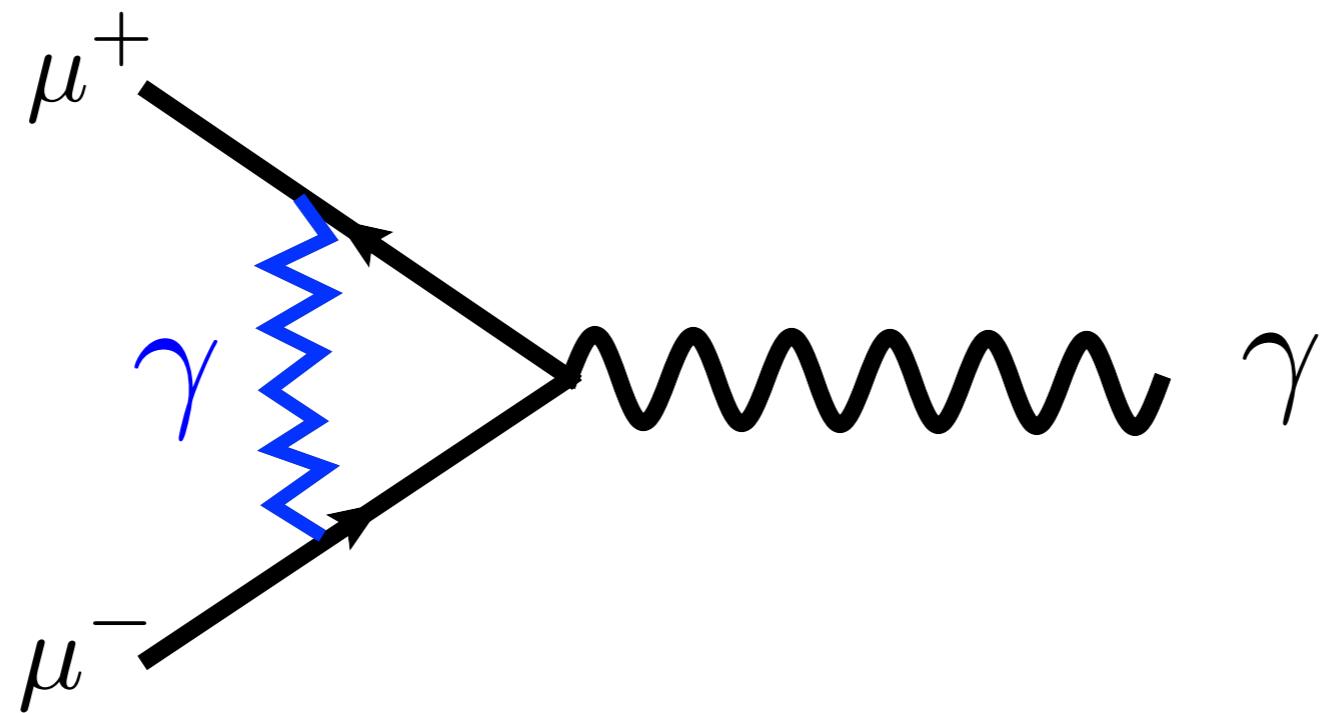
Pospelov  
Boehm, Fayet

$A'$  may explain observed  $(g_s - 2)_\mu$ !

contribution depends on only 2 parameters:

$\epsilon$  and  $m_{A'}$

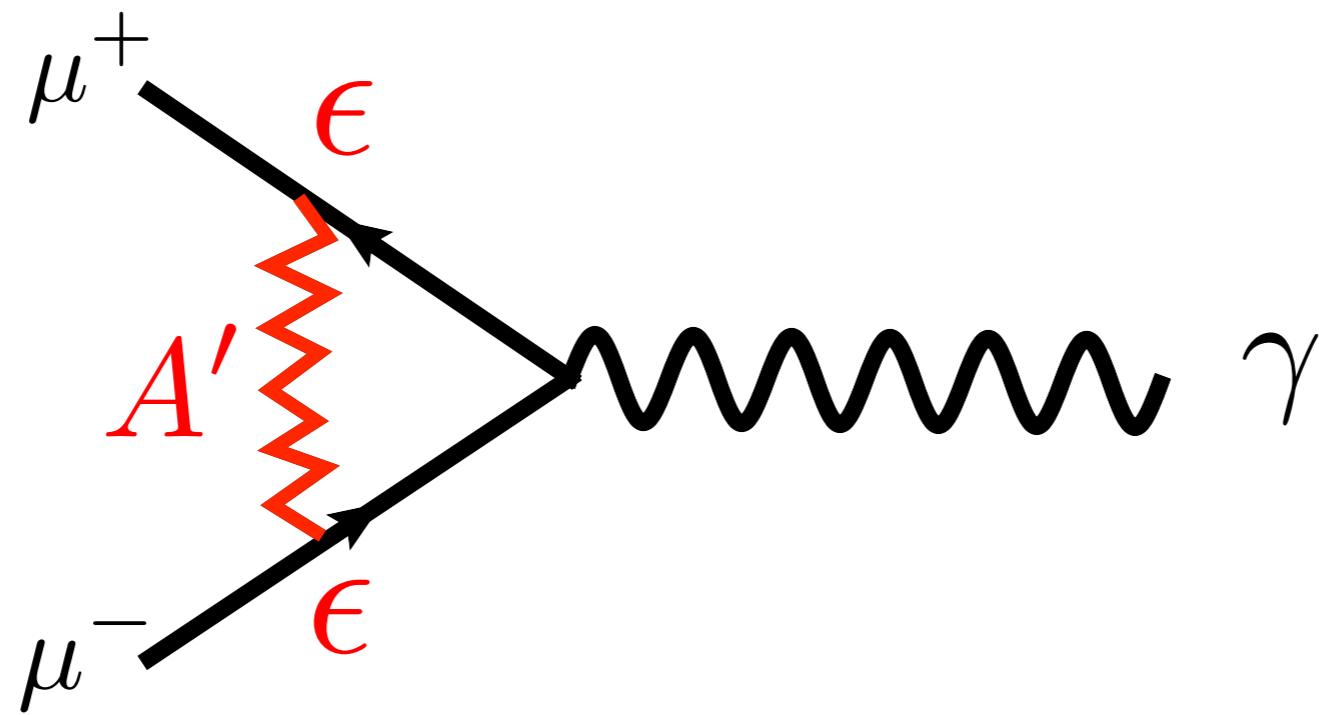
# Muon's anomalous magnetic moment?



Recall: photon contribution is

$$(g_s - 2)_\mu^\gamma \simeq \frac{\alpha}{2\pi}$$
$$\simeq 10^{-3}$$

# Muon's anomalous magnetic moment?

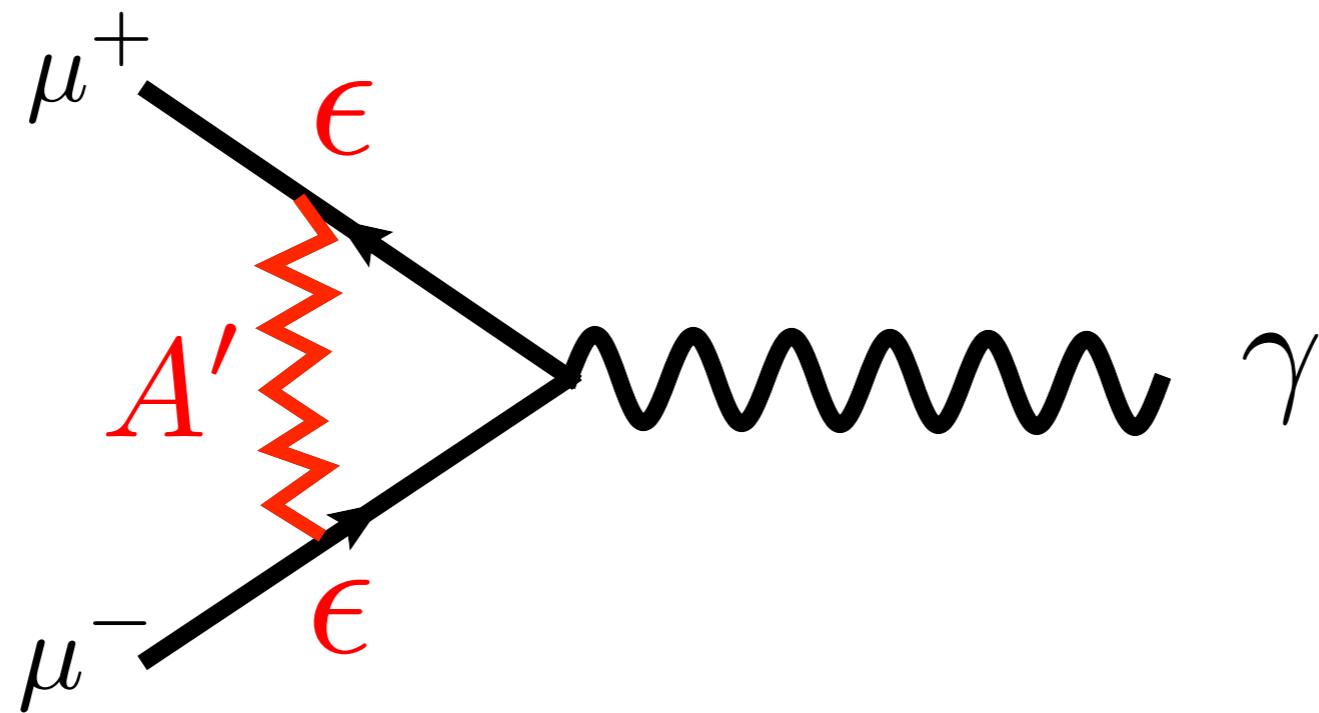


Pospelov  
Boehm, Fayet

**$A'$  contribution is:**

$$(g_s - 2)_\mu^{A'} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \quad (m_{A'} \ll m_\mu)$$
$$\simeq 10^{-3} \times \epsilon^2$$

# Muon's anomalous magnetic moment?



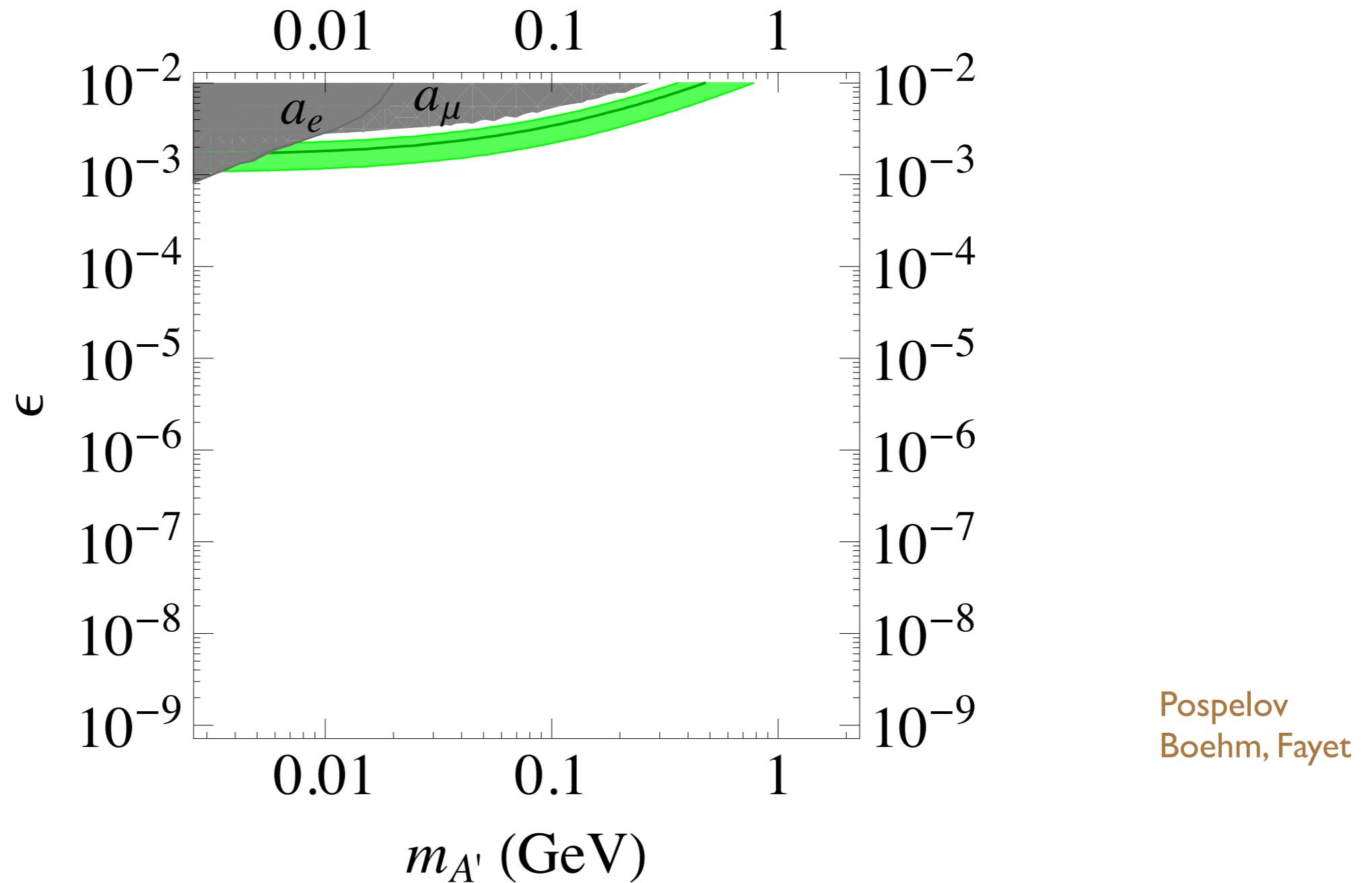
Pospelov  
Boehm, Fayet

**$A'$  contribution is:**

$$(g_s - 2)_\mu^{A'} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \quad (m_{A'} \ll m_\mu)$$
$$\simeq 10^{-3} \times \epsilon^2$$

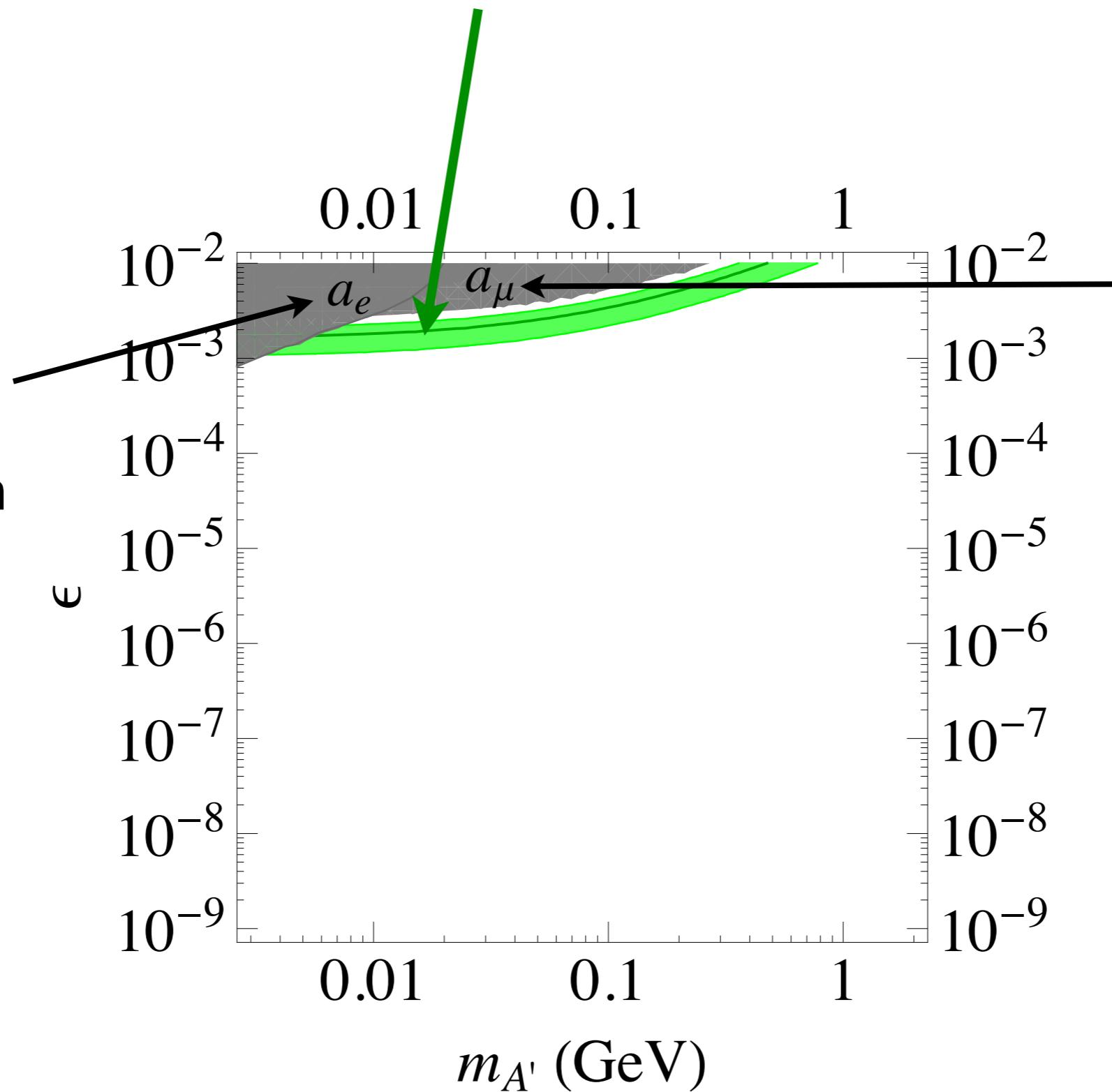
SM/data discrepancy is  $\sim 10^{-9}$  so need  $\epsilon \sim 10^{-3}$

# A' may explain observed $(g_s - 2)_\mu$



# A' may explain observed $(g_s - 2)_\mu$

constraint  
from  $g_s-2$   
for electron



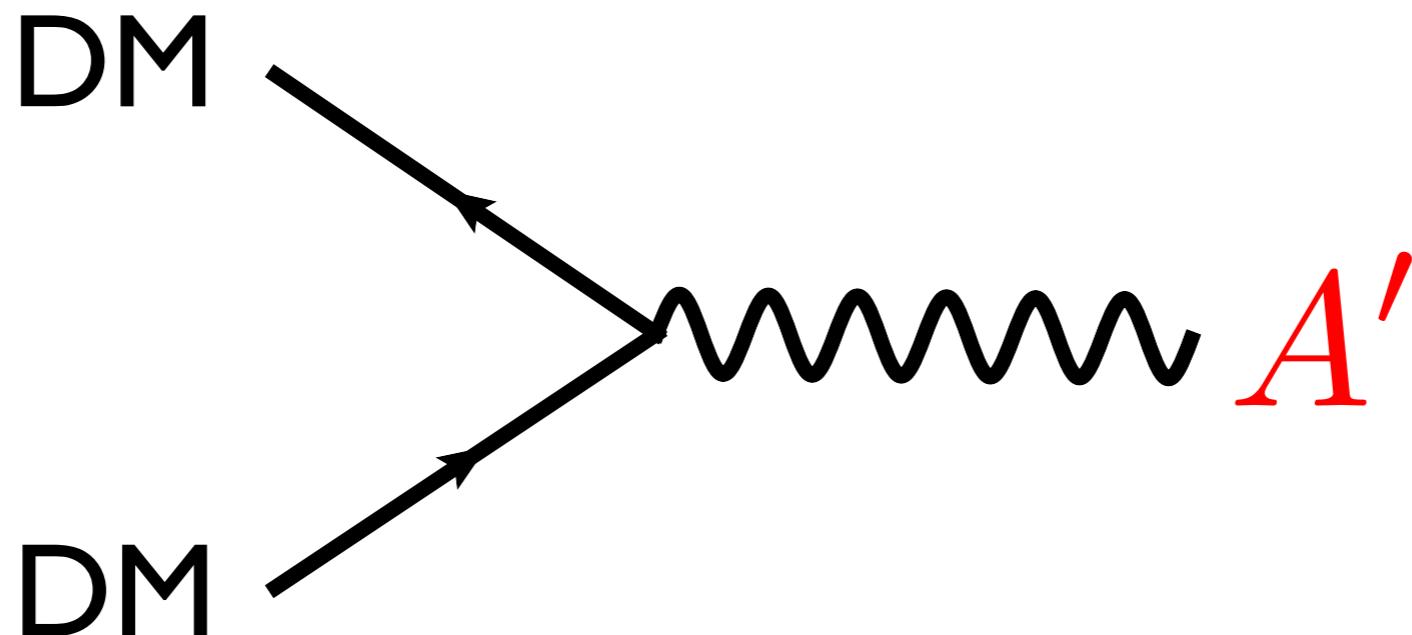
constraint  
from  $g_s-2$   
for muon

Pospelov  
Boehm, Fayet

# More hints for an $A'$

(Speculative, but amazing if true)

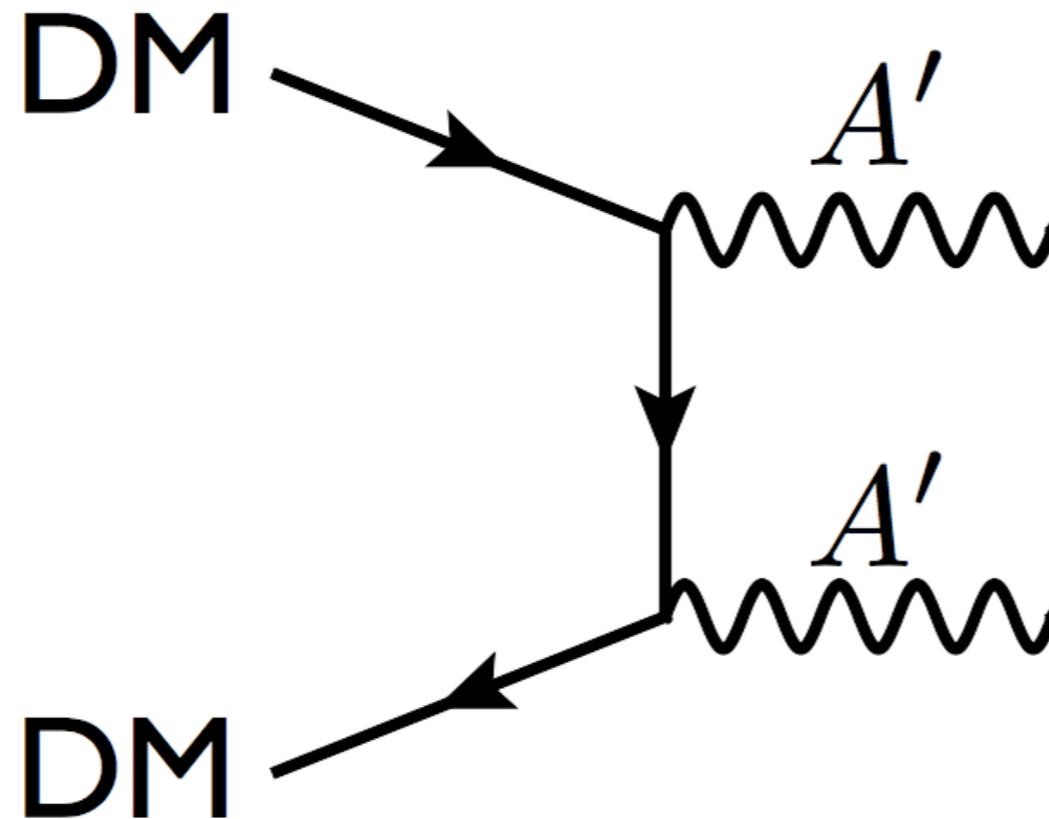
What if dark matter couples to  $A'$  ?



Provides new interaction between  
dark matter and ordinary matter!

# Dark matter can annihilate to A's

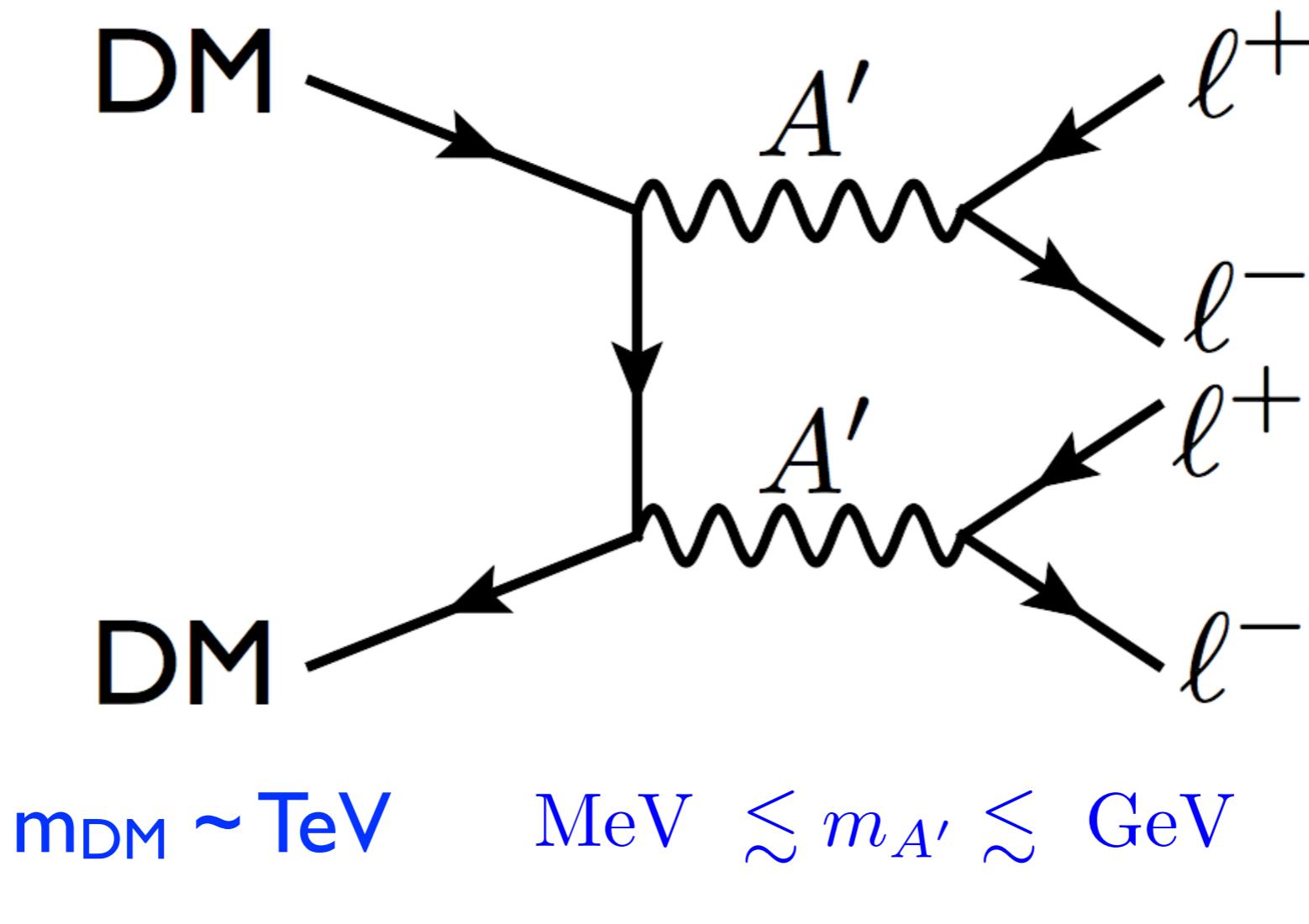
Arkani-Hamed, Finkbeiner, Slatyer, Weiner;  
Pospelov & Ritz; Finkbeiner & Weiner;  
Cholis, Goodenough, Weiner;



$$m_{\text{DM}} \sim \text{TeV} \quad \text{MeV} \lesssim m_{A'} \lesssim \text{GeV}$$

# Dark matter can annihilate to A's

Arkani-Hamed, Finkbeiner, Slatyer, Weiner;  
Pospelov & Ritz; Finkbeiner & Weiner;  
Cholis, Goodenough, Weiner;

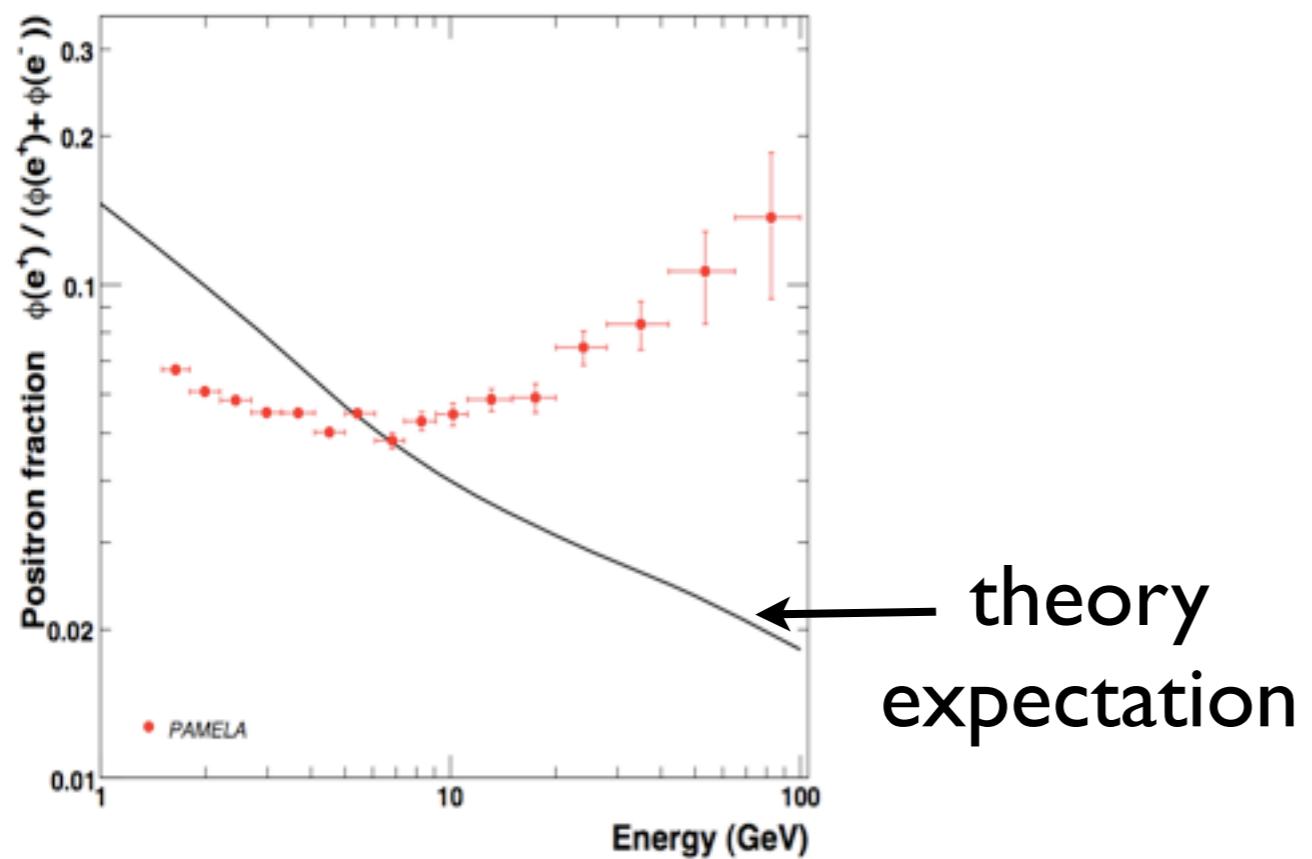


produces high-energy ( $\sim 100$  GeV)  
cosmic-ray electrons and positrons

# Could explain cosmic-ray excesses?

Arkani-Hamed, Finkbeiner, Slatyer, Weiner;  
Pospelov & Ritz; Finkbeiner & Weiner;  
Cholis, Goodenough, Weiner;

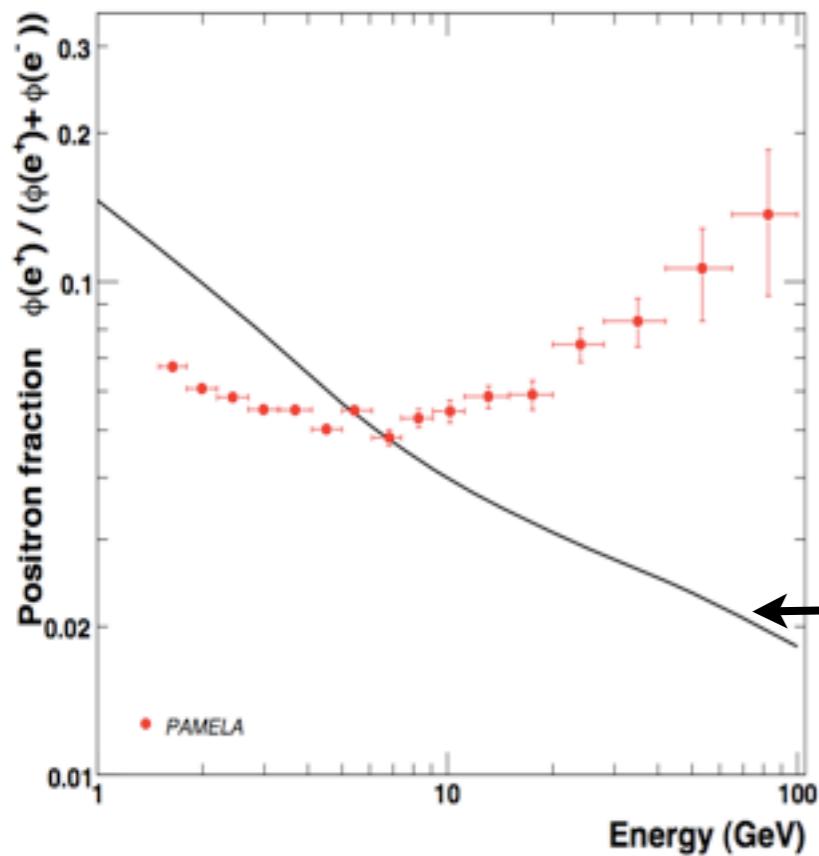
PAMELA:  
 $e^+$  excess



# Could explain cosmic-ray excesses?

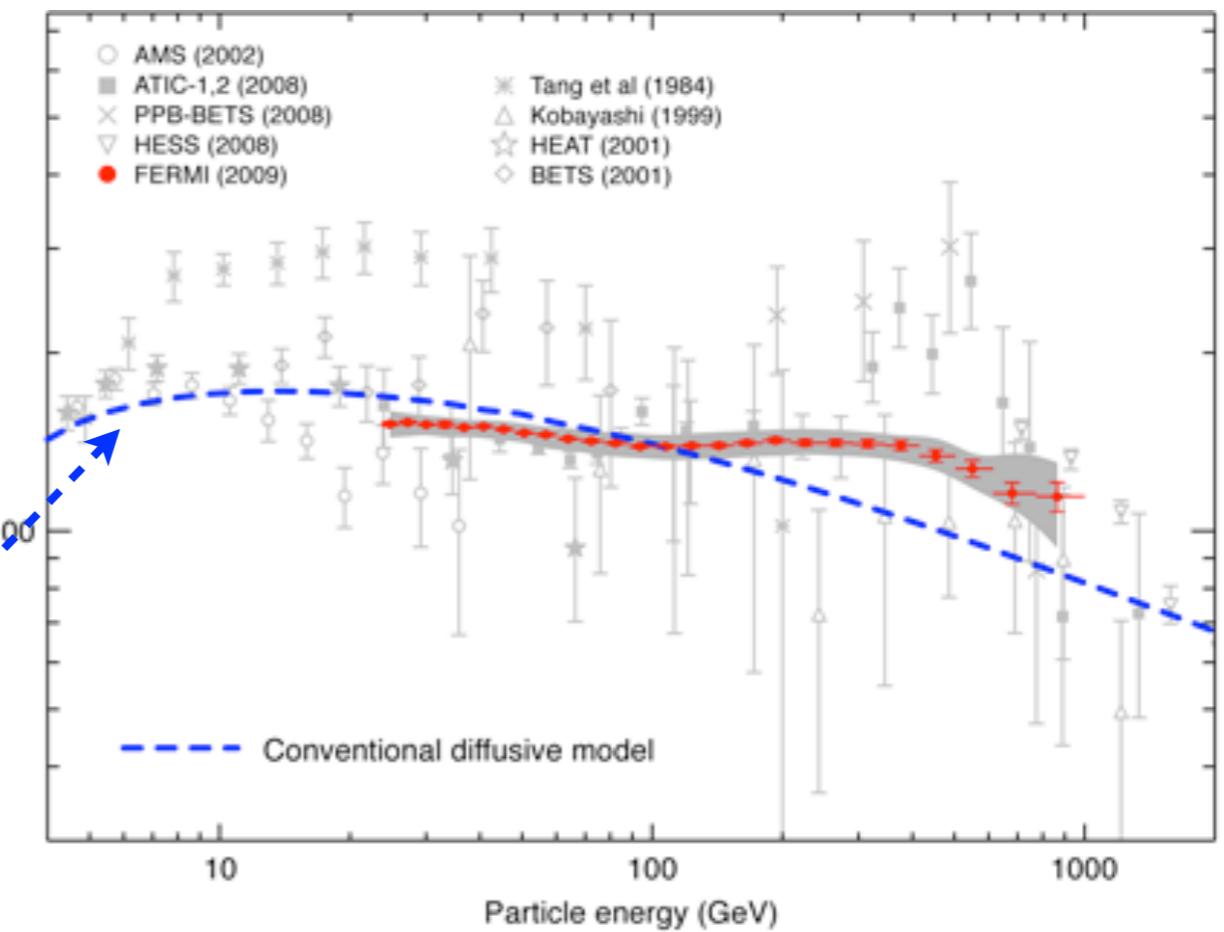
Arkani-Hamed, Finkbeiner, Slatyer, Weiner;  
Pospelov & Ritz; Finkbeiner & Weiner;  
Cholis, Goodenough, Weiner;

PAMELA:  
 $e^+$  excess



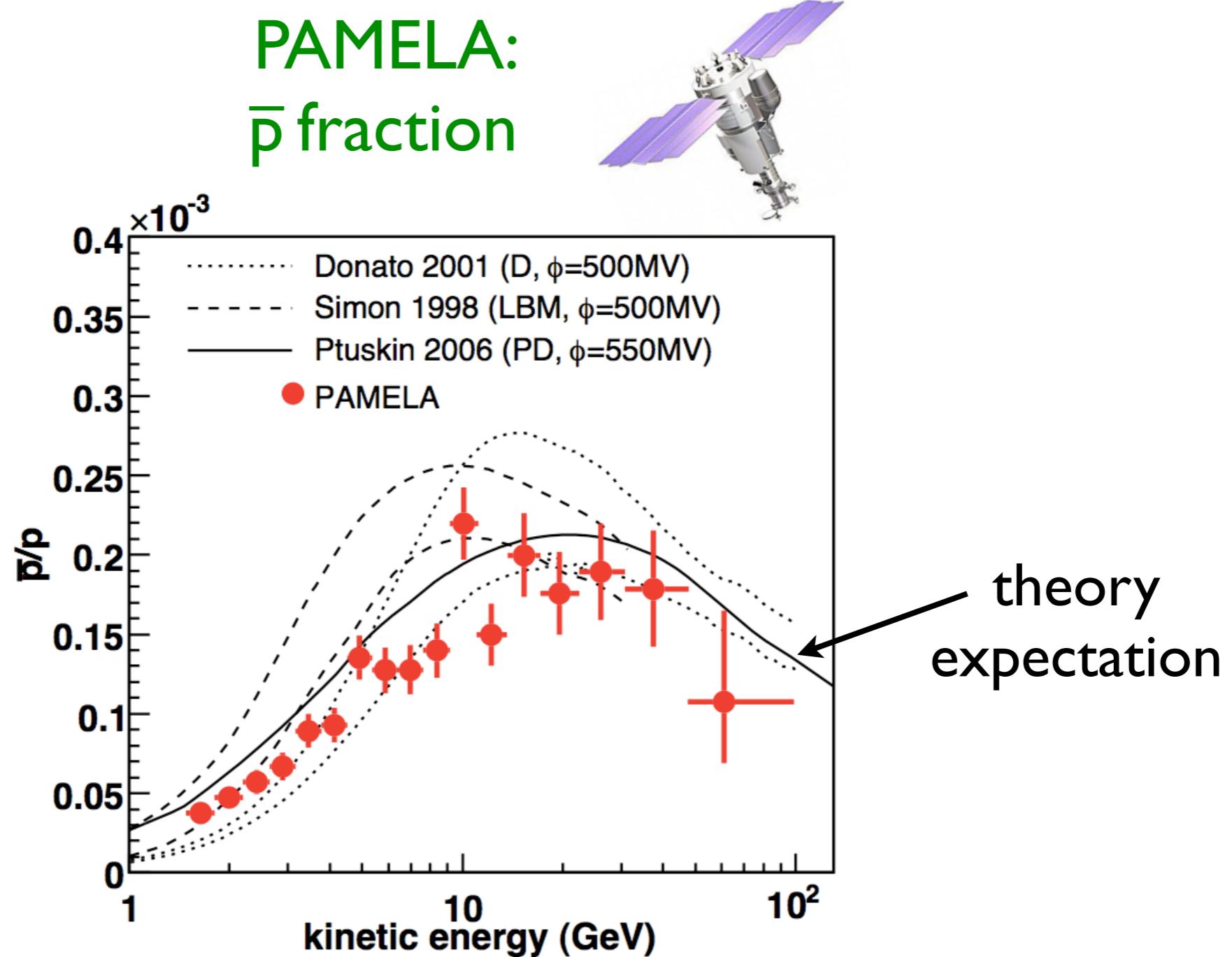
theory  
expectation

Fermi:  
 $e^+ + e^-$  excess

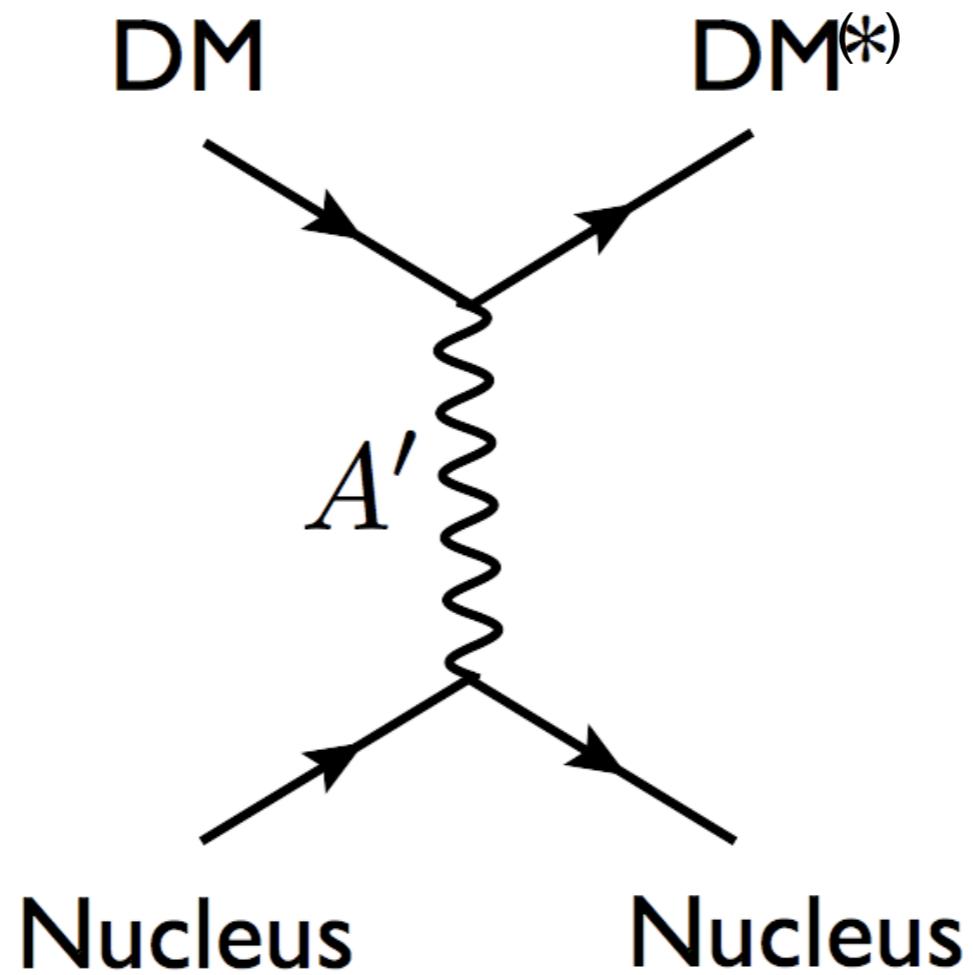


# ...and explain absence of antiproton excess?

Arkani-Hamed, Finkbeiner, Slatyer, Weiner;  
Pospelov & Ritz; Finkbeiner & Weiner;  
Cholis, Goodenough, Weiner;



# Dark matter can also scatter off nuclei



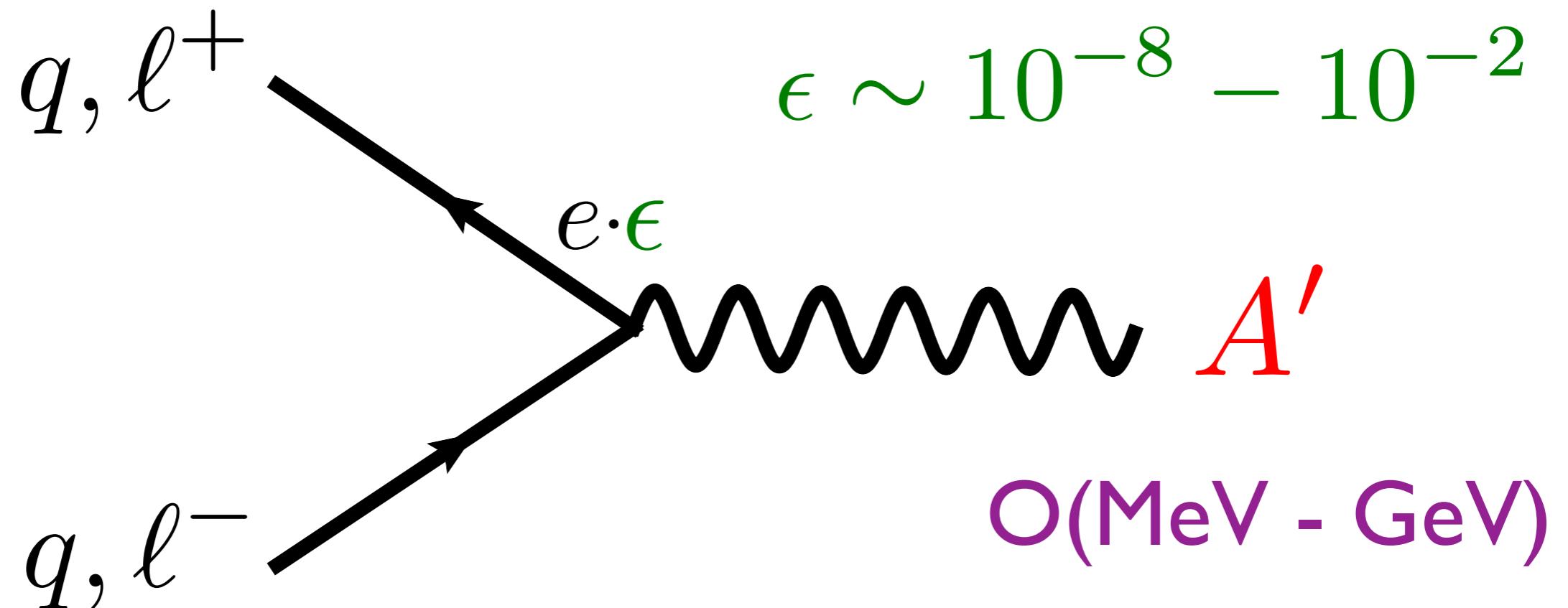
Tucker-Smith & Weiner;  
Arkani-Hamed et.al.;  
Cheung, Ruderman, Wang, Yavin;  
Morrissey, Poland, Zurek;  
RE, Kaplan, Schuster, Toro;  
...

explain anomalies in direct  
detection experiments?

(e.g. DAMA, CoGeNT, CRESST)

# Summary

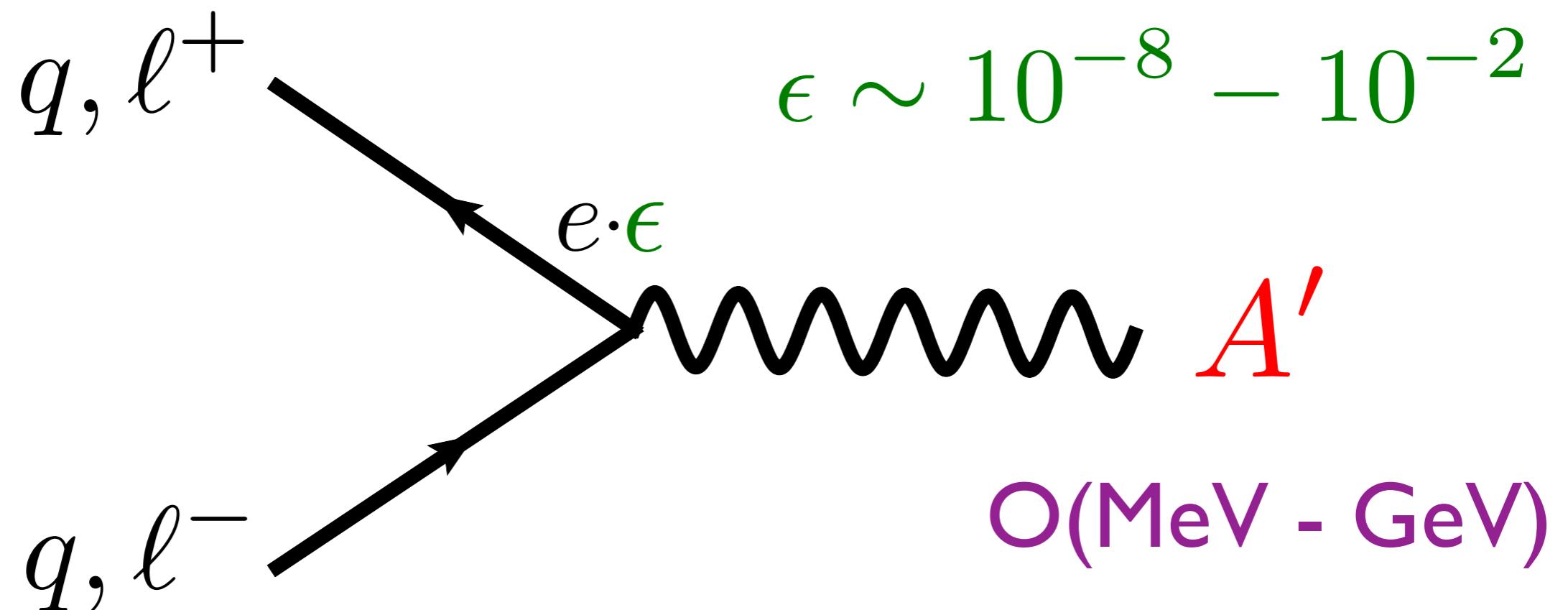
Quarks & charged Leptons couple to  $A'$



Theoretically natural  
Hints from  $(g_s - 2)$ , dark matter anomalies, ...

# Summary

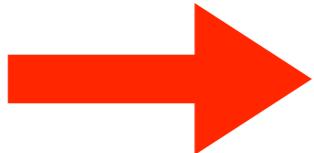
Quarks & charged Leptons couple to  $A'$



Theoretically natural  
Hints from  $(g_s - 2)$ , dark matter anomalies, ...

So how can we search for an  $A'$  ?

# Outline

- Theory
  - Motivation (“hints”)
  - Searches
    - $e^+e^-$  colliders
    - fixed target:  $e^-$  and  $p$
    - Tevatron & LHC
- 

Many possibilities, will only highlight a few !

# Outline

- Theory
- Motivation (“hints”)
- Searches
  - •  $e^+e^-$  colliders
  - • fixed target:  $e^-$  and  $p$
  - Tevatron & LHC

# Produce A' in $e^+e^-$ collisions

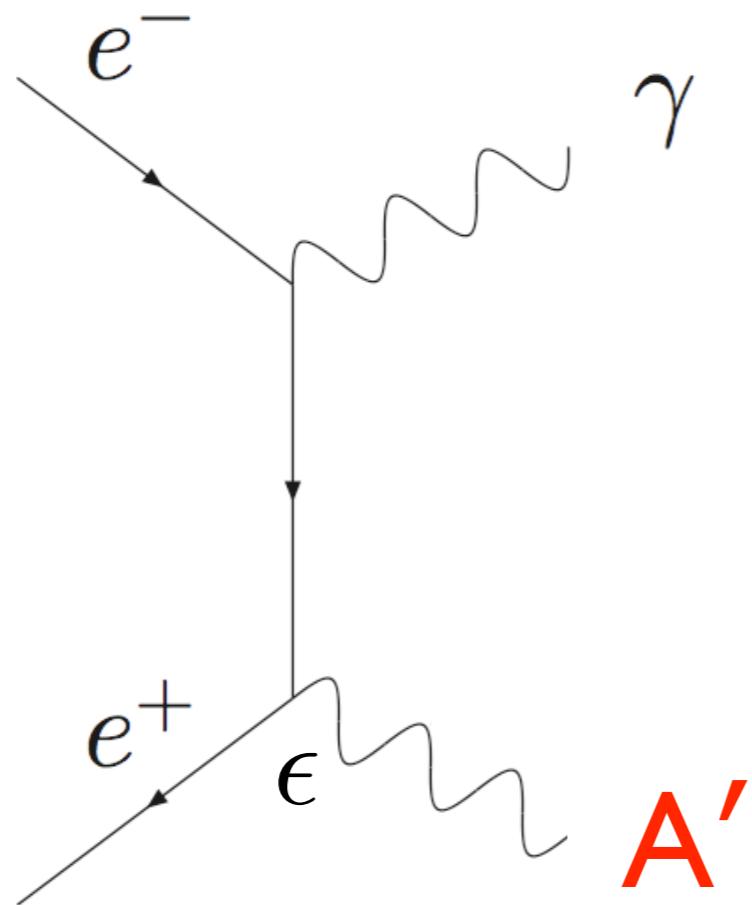
RE, Schuster, Toro

Batell, Pospelov, Ritz

Reece, Wang

Borodatchenkova et.al.

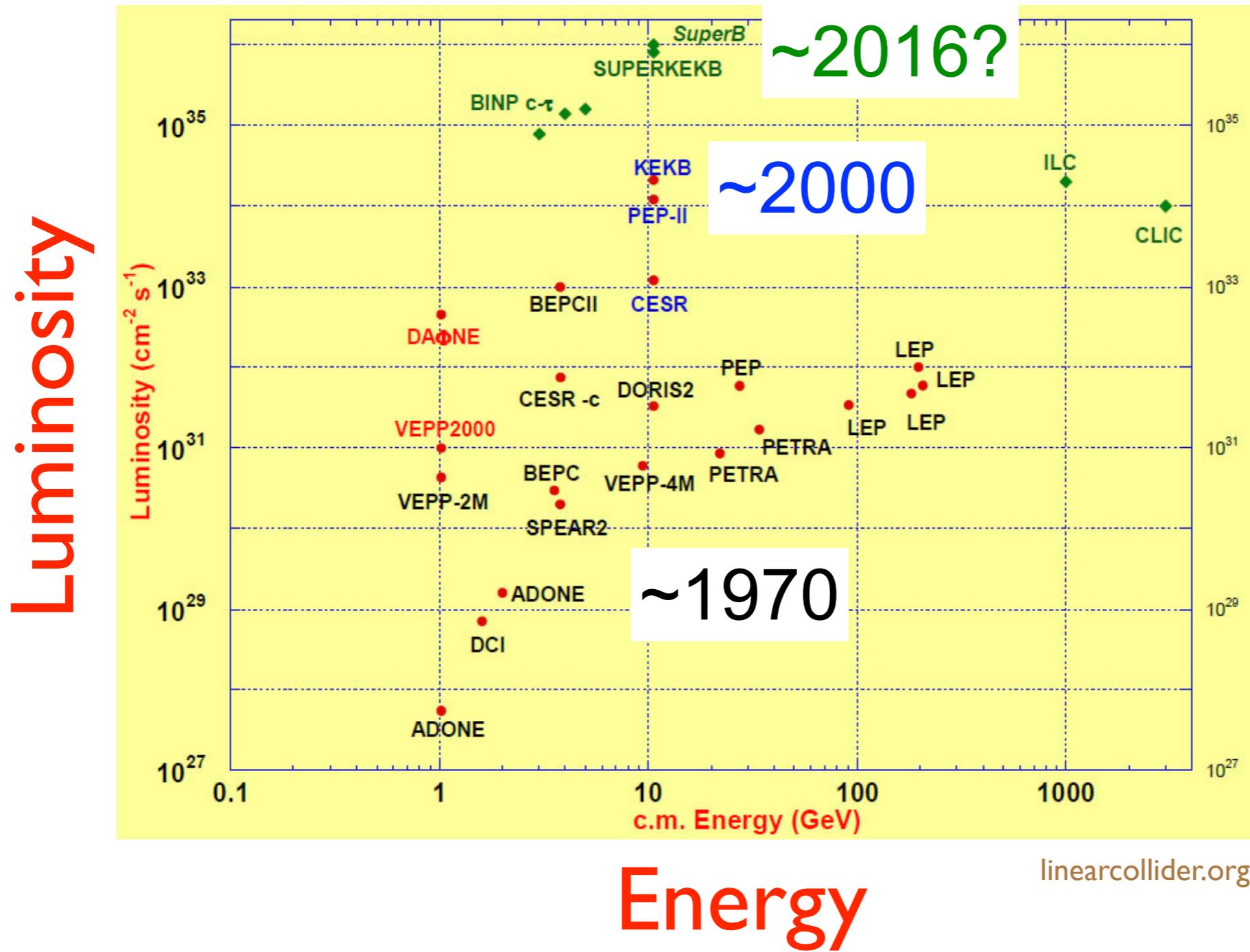
Fayet



$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2}$$

want low-energy (1-10 GeV), high intensity  
colliders (BaBar, BELLE, KLOE, ...)

# e<sup>+</sup>e<sup>-</sup> colliders

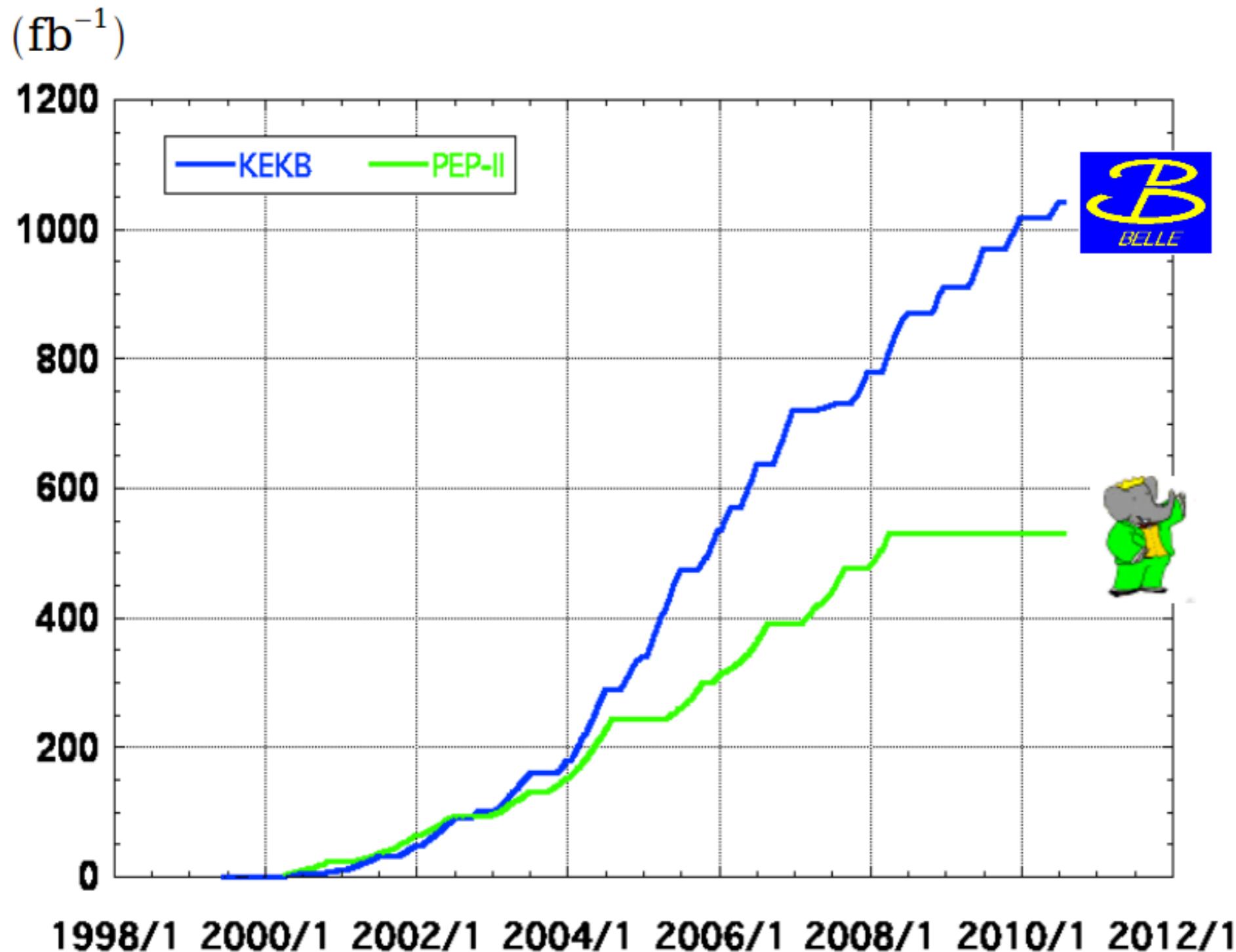


Energy

[linearcollider.org](http://linearcollider.org)

enormous increase in luminosity over last few decades

# Integrated luminosity of B-factories



$> 1 \text{ ab}^{-1}$

**On resonance:**

$Y(5S): 121 \text{ fb}^{-1}$

$Y(4S): 711 \text{ fb}^{-1}$

$Y(3S): 3 \text{ fb}^{-1}$

$Y(2S): 25 \text{ fb}^{-1}$

$Y(1S): 6 \text{ fb}^{-1}$

**Off reson./scan:**

$\sim 100 \text{ fb}^{-1}$

$\sim 550 \text{ fb}^{-1}$

**On resonance:**

$Y(4S): 433 \text{ fb}^{-1}$

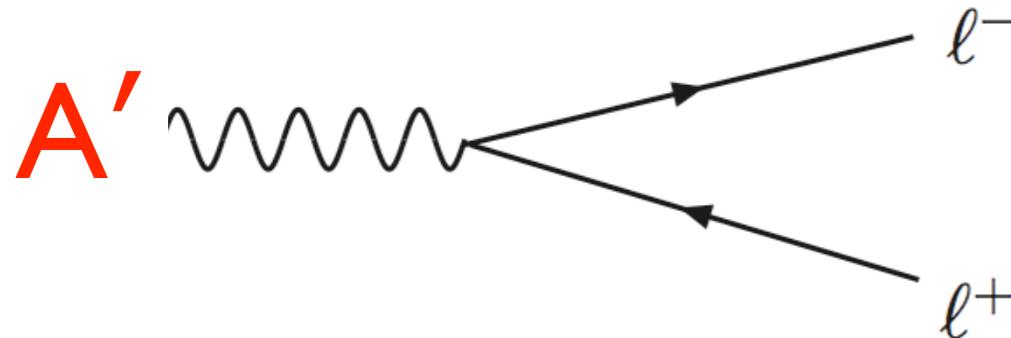
$Y(3S): 30 \text{ fb}^{-1}$

$Y(2S): 14 \text{ fb}^{-1}$

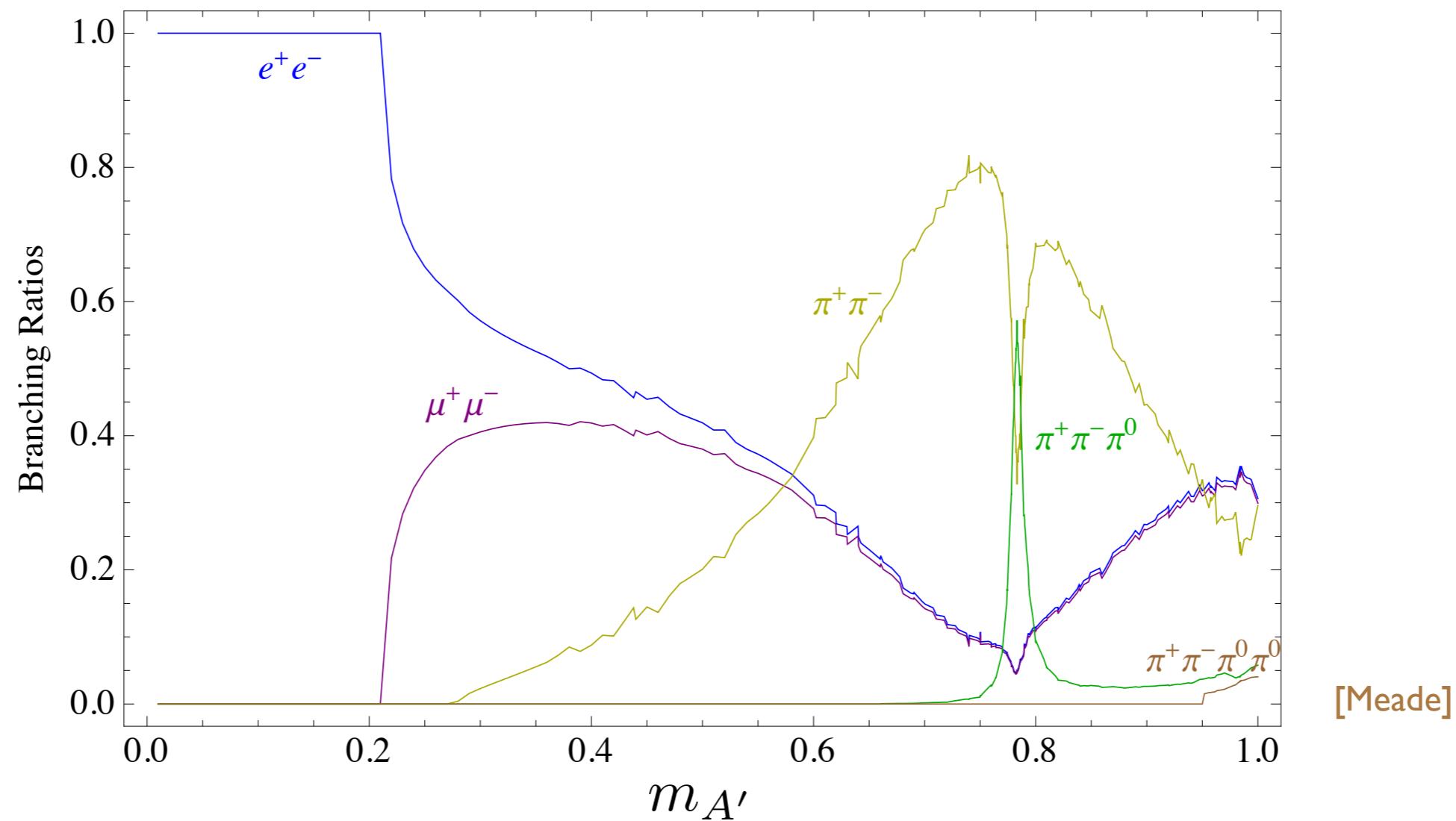
**Off resonance:**

$\sim 54 \text{ fb}^{-1}$

# A' can decay directly to Standard Model



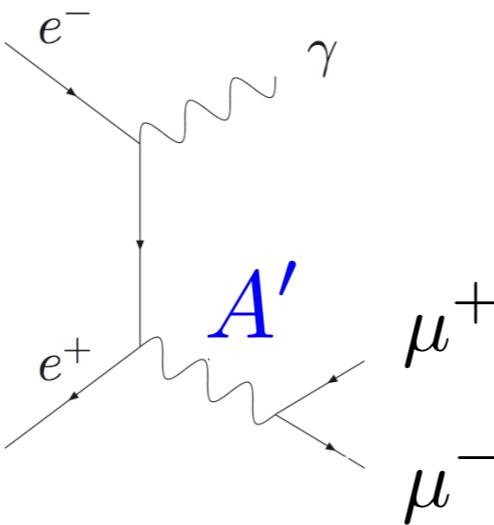
$(A' \rightarrow \text{hidden sector also possible})$



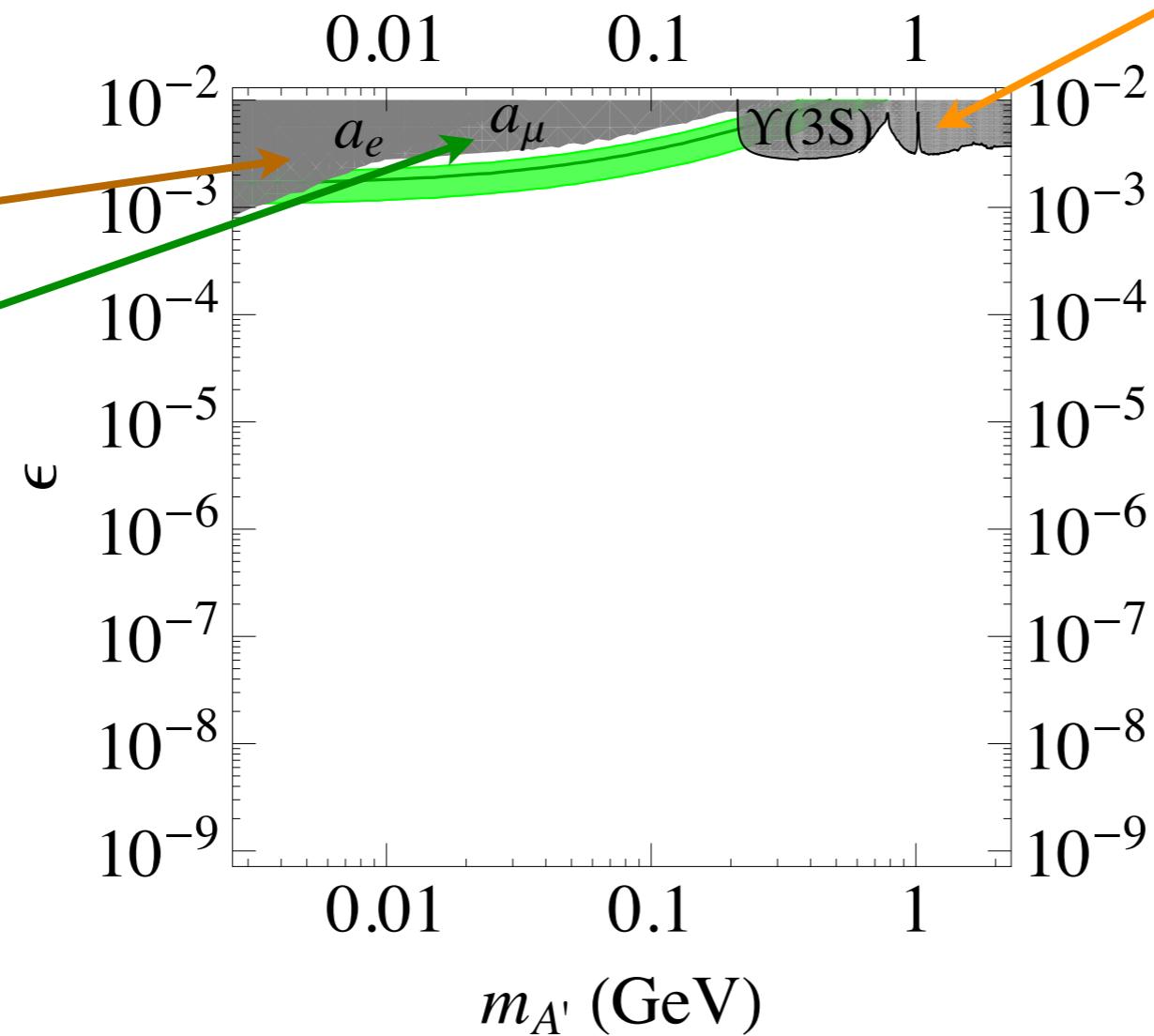
Broad array of searches needed and underway

# Constraint

RE, Schuster, Toro, Wojtsekhowski  
Reece, Wang



g-2 for  
electron  
and muon

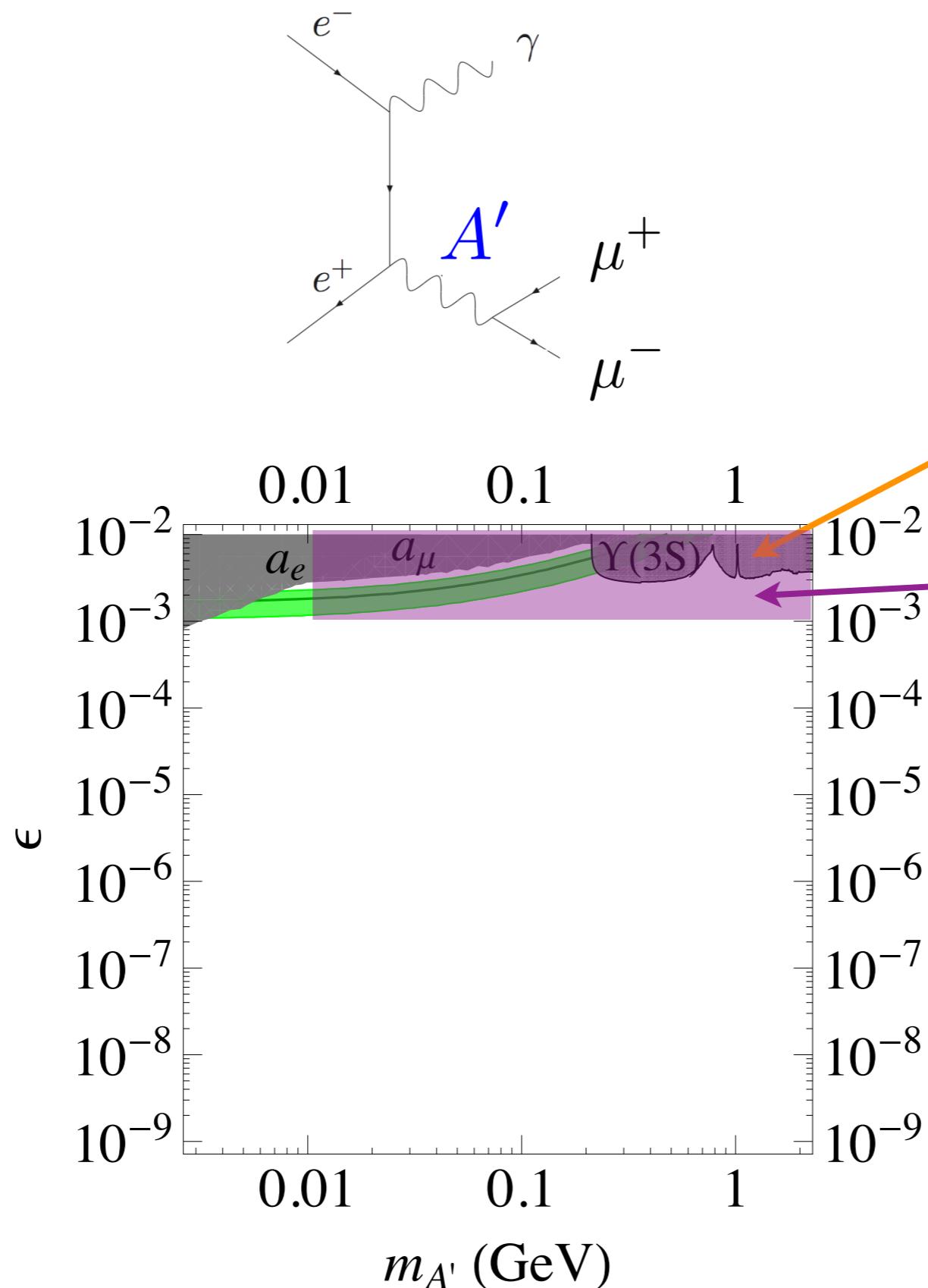


BaBar  
(partial data set)

# Constraint

RE, Schuster, Toro, Wojtsekhowski

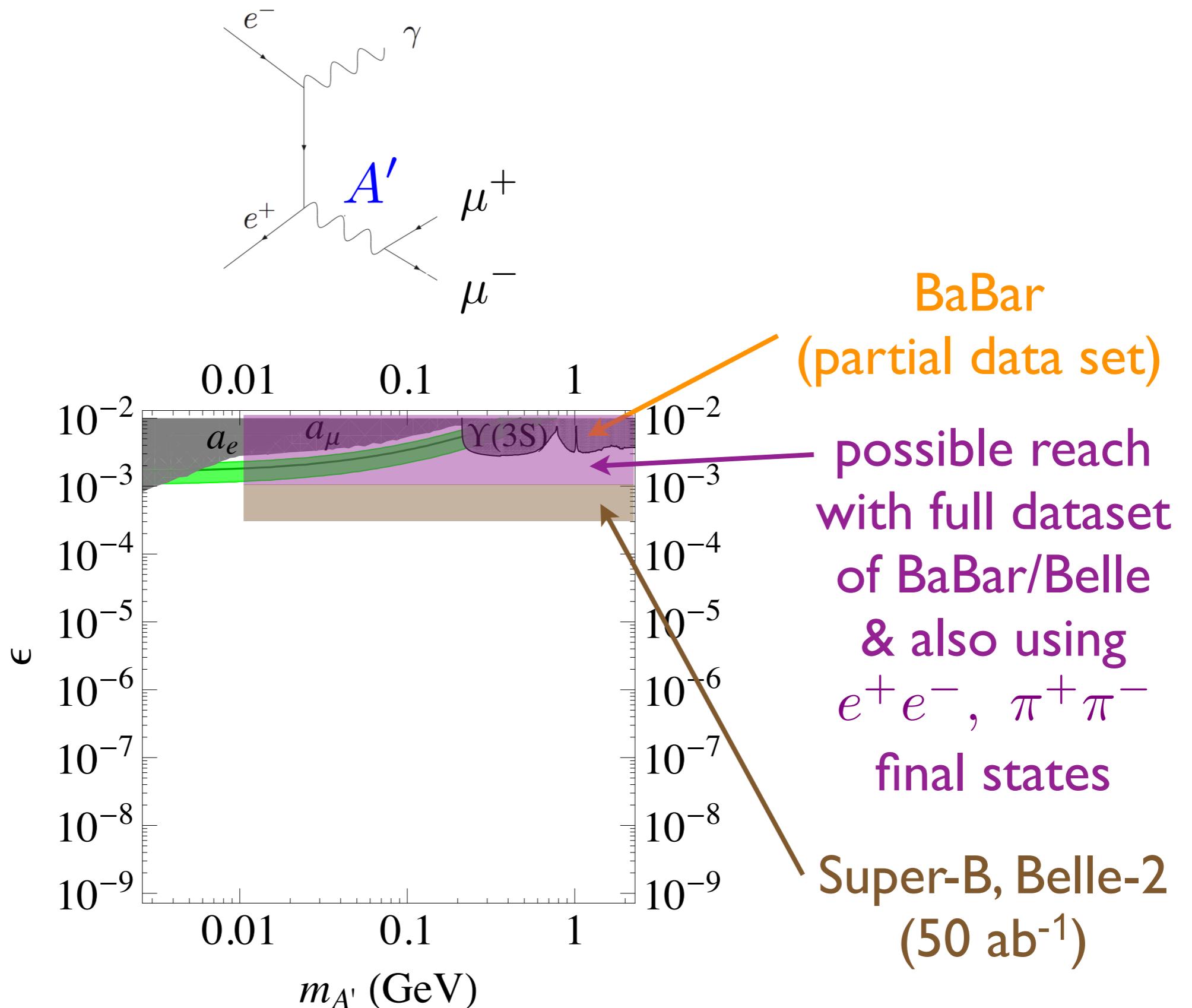
Reece, Wang



# Constraint

RE, Schuster, Toro, Wojtsekhowski

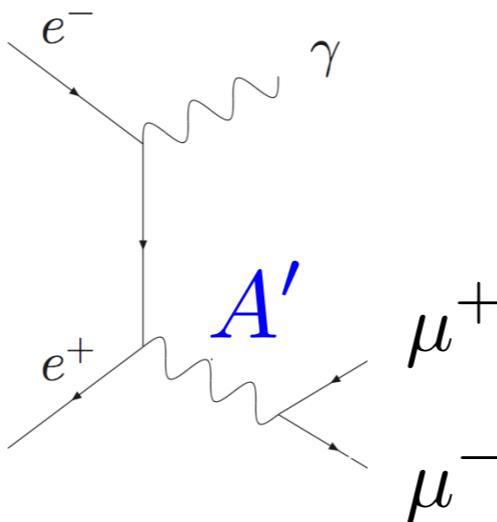
Reece, Wang



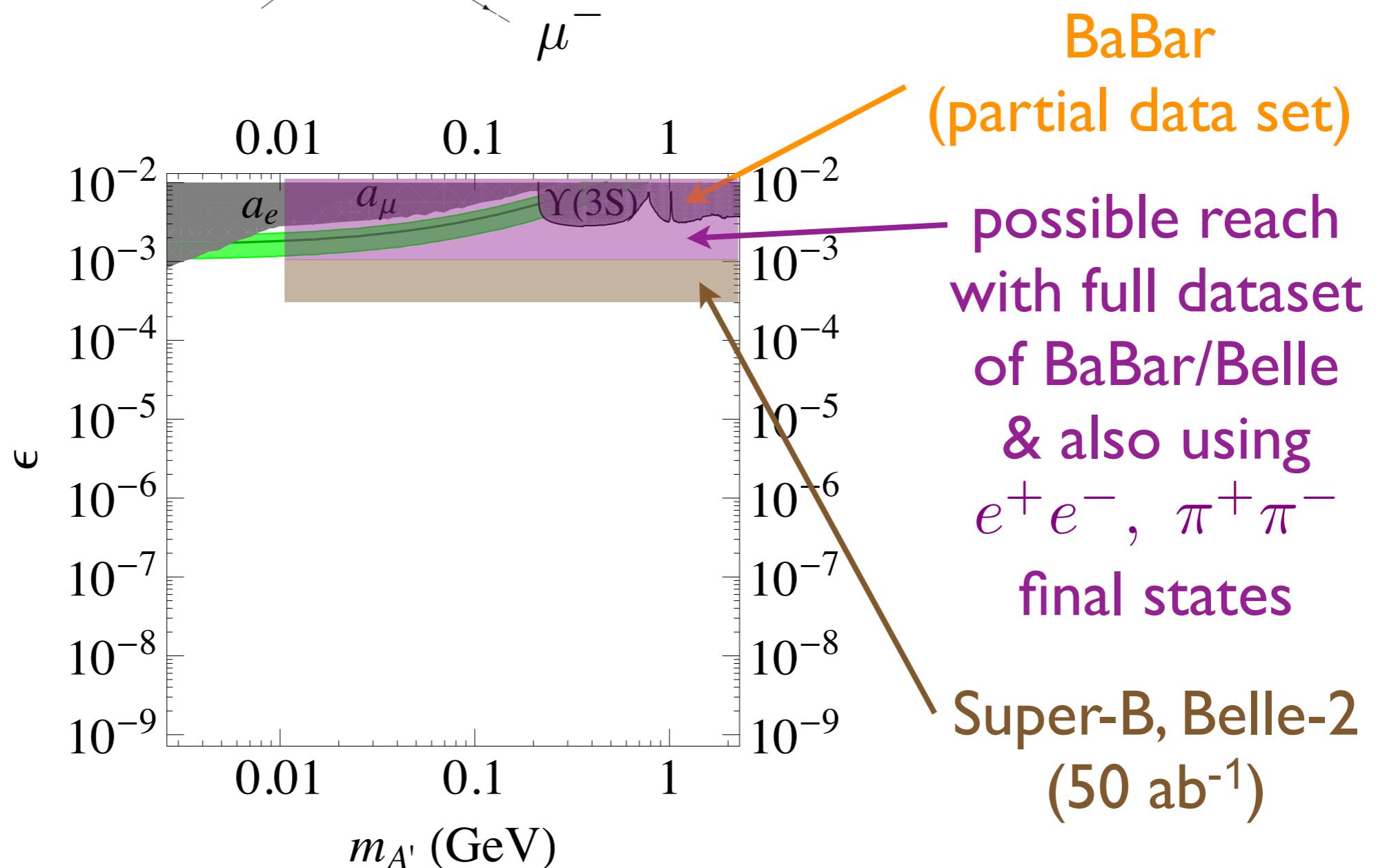
# Constraint

RE, Schuster, Toro, Wojtsekhowski

Reece, Wang



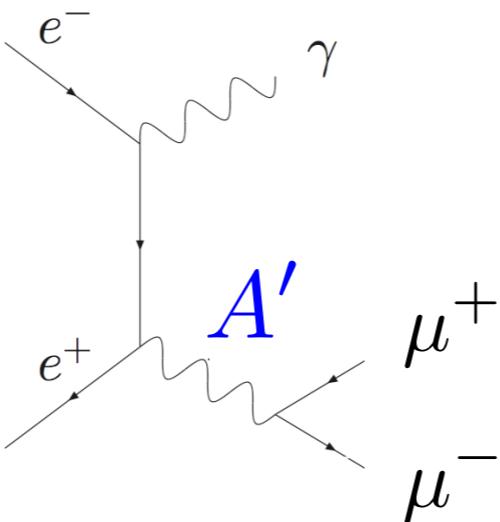
probes  
g<sub>s</sub>-2 region!



# Constraint

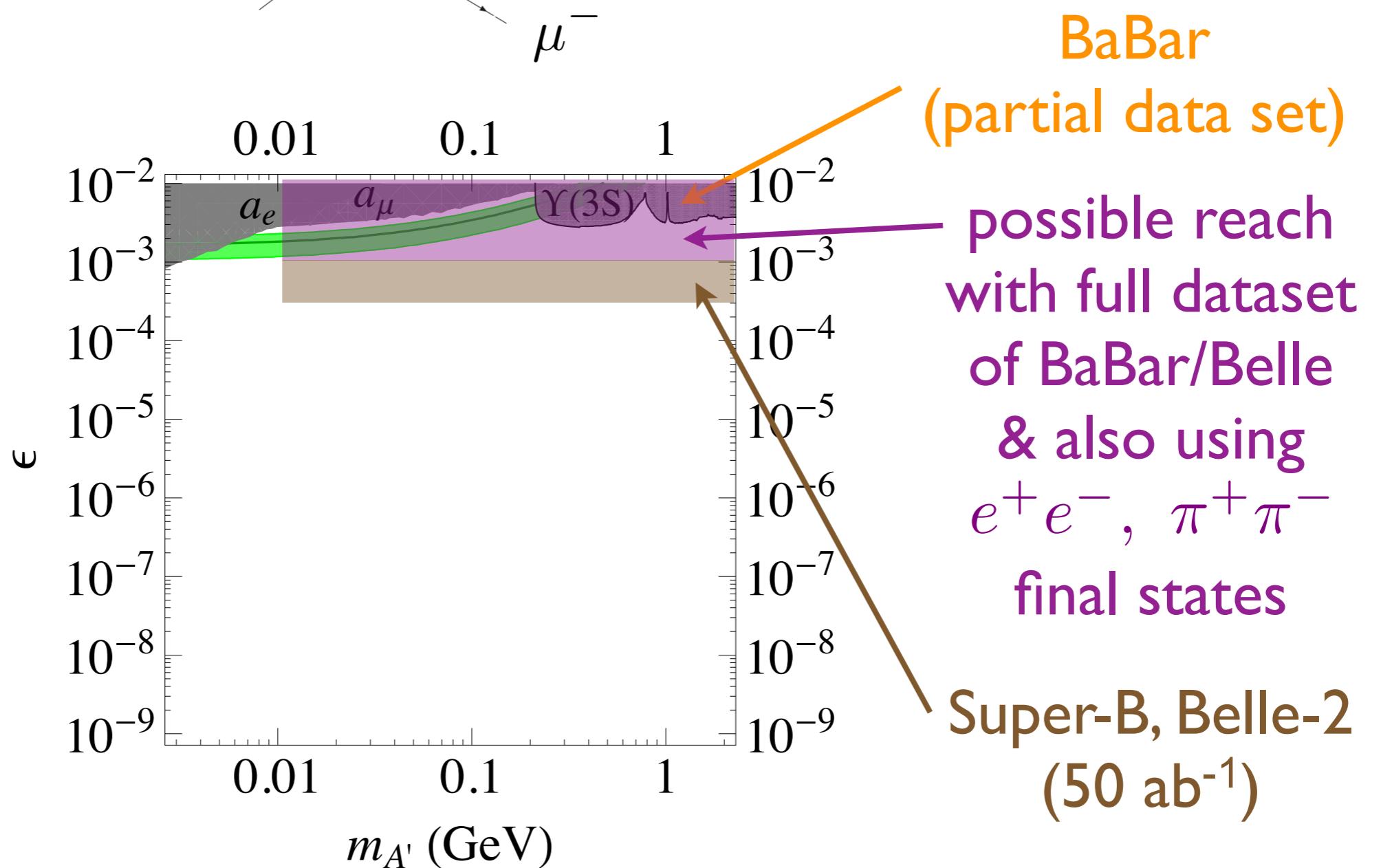
RE, Schuster, Toro, Wojtsekhowski

Reece, Wang



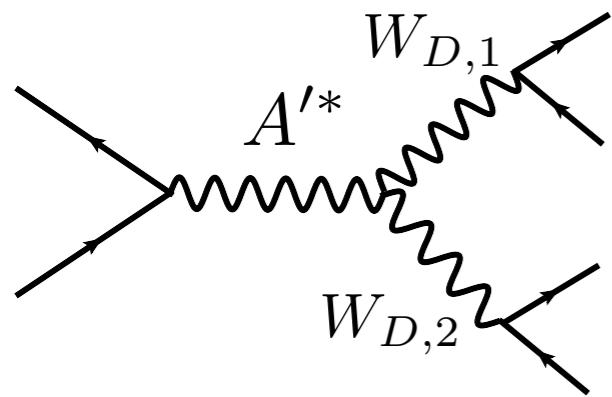
probes  
g<sub>s</sub>-2 region!

*Caveat:*  
assumes  
A' decays  
directly to  
Standard  
Model !



Need other searches, for example:

# Need other searches, for example:



Done

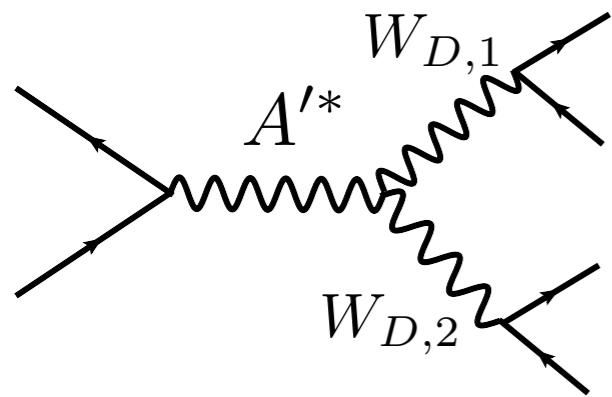
$4e, 4\mu, 2e + 2\mu$

BaBar

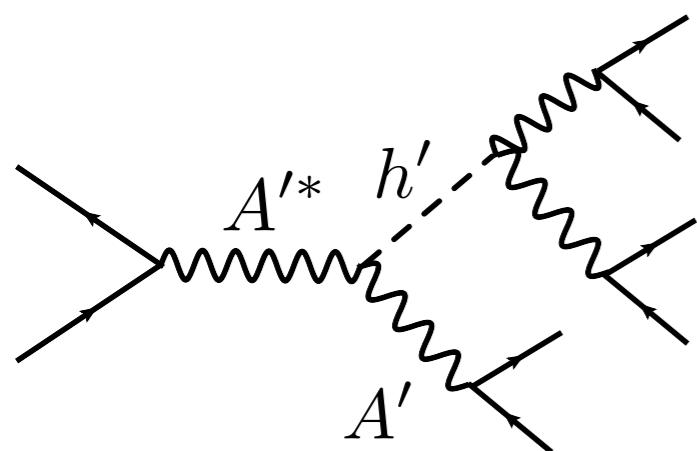
[Graham & Roodman]

non-Abelian hidden sectors  
(many gauge bosons)

# Need other searches, for example:



non-Abelian hidden sectors  
(many gauge bosons)



light hidden-sector  
Higgs boson

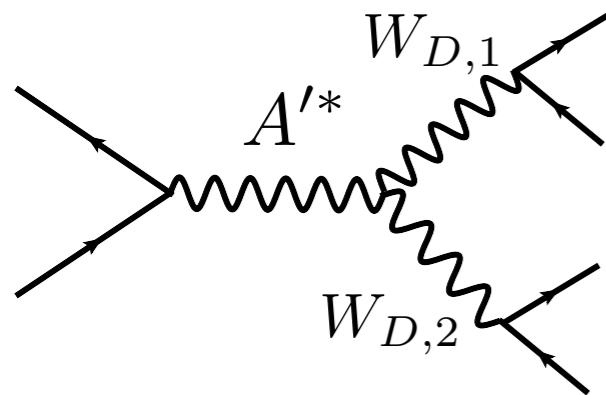
Done  
 $4e, 4\mu, 2e + 2\mu$

BaBar  
[Graham & Roodman]

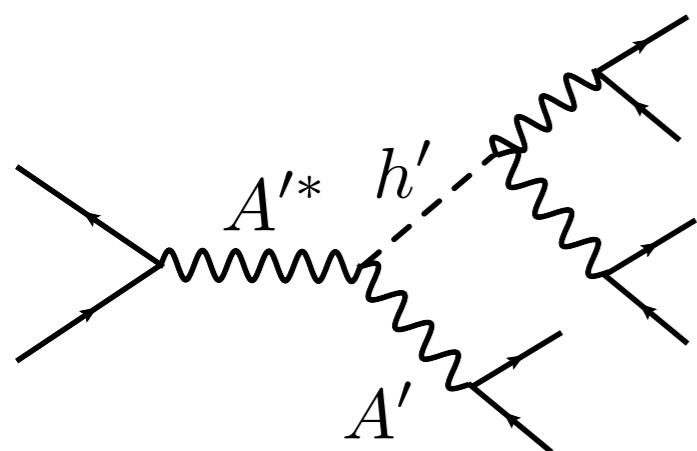
In progress  
 $2\ell, 6\ell$

Higgs'-strahlung  
[Batell, Pospelov, Ritz]

# Need other searches, for example:



non-Abelian hidden sectors  
(many gauge bosons)



light hidden-sector  
Higgs boson

Done

$4e, 4\mu, 2e + 2\mu$

BaBar

[Graham & Roodman]

In progress

$2\ell, 6\ell$

Higgs'-strahlung

[Batell, Pospelov, Ritz]

multi-lepton + pion searches also in progress

Pospelov  
Reece,Wang  
Batell, Pospelov,Ritz  
RE, Schuster,Toro,  
Wojtsekhowski

# Rare meson decays

Many possibilities... e.g.

$$\phi \rightarrow \eta A' \quad A' \rightarrow e^+ e^- \quad \eta \rightarrow \pi^+ \pi^- \pi^0$$

Pospelov  
Reece,Wang  
Batell, Pospelov,Ritz  
RE, Schuster,Toro,  
Wojtsekhowski

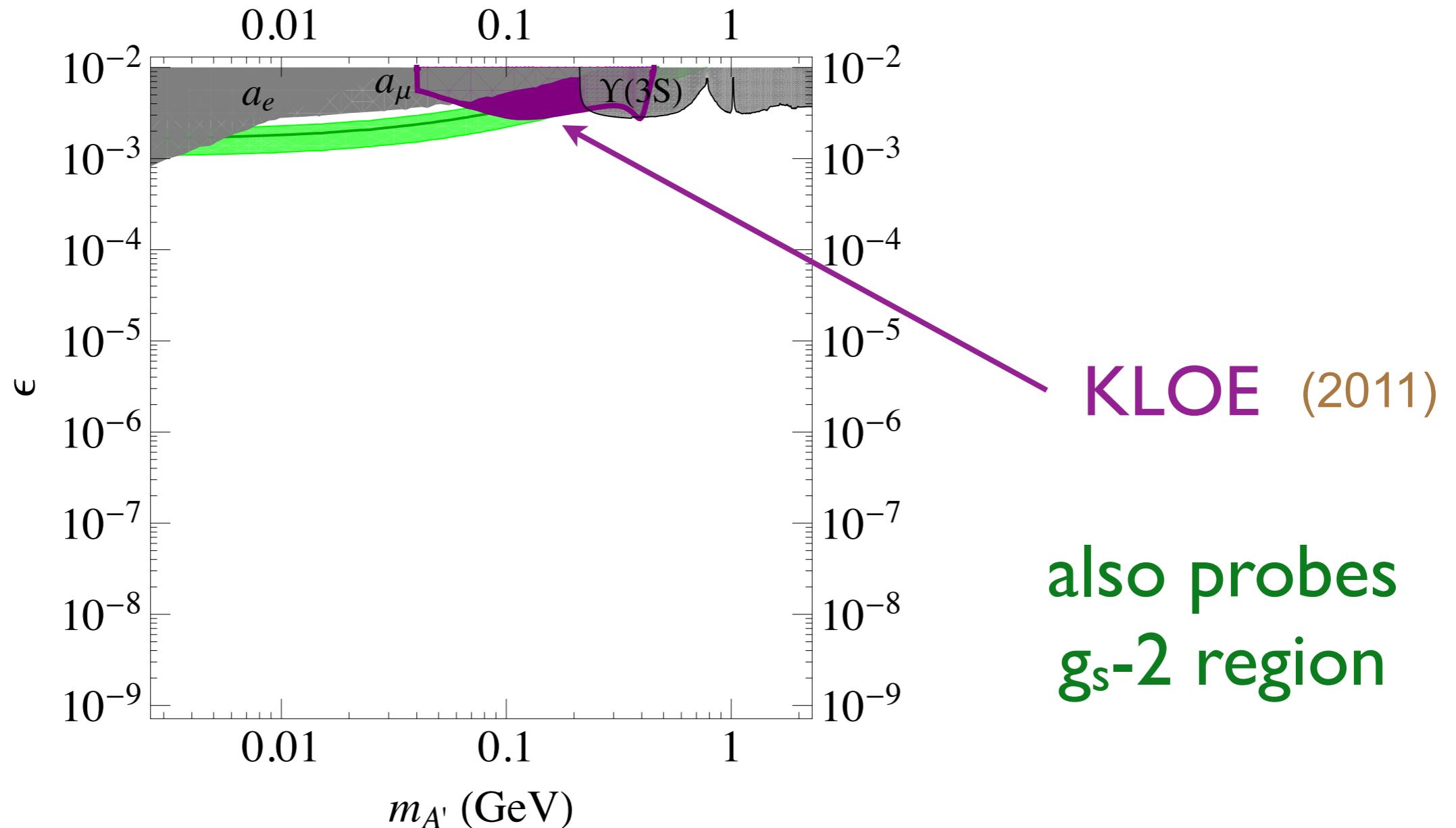
# Rare meson decays

Many possibilities... e.g.

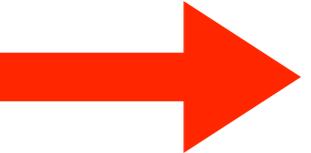
$$\phi \rightarrow \eta A'$$

$$A' \rightarrow e^+ e^-$$

$$\eta \rightarrow \pi^+ \pi^- \pi^0$$



# Outline

- Theory
  - Motivation (“hints”)
  - Searches
    - $e^+e^-$  colliders
    - fixed target:  $e^-$  and  $p$
    - Tevatron & LHC
- 
- 

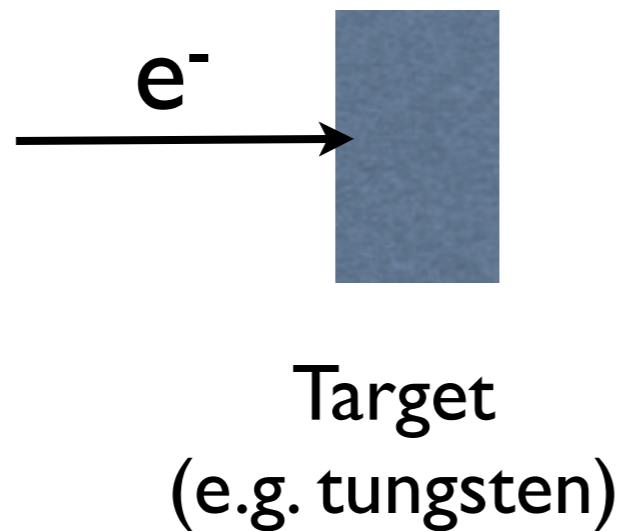
# Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce A' via bremsstrahlung off  $e^-$  beam on fixed target



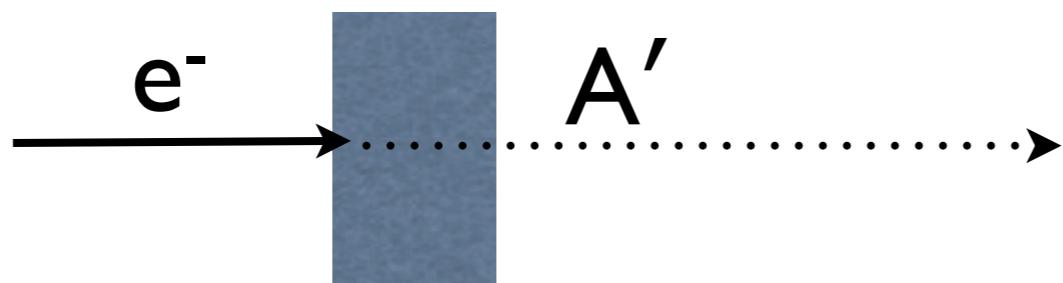
# Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

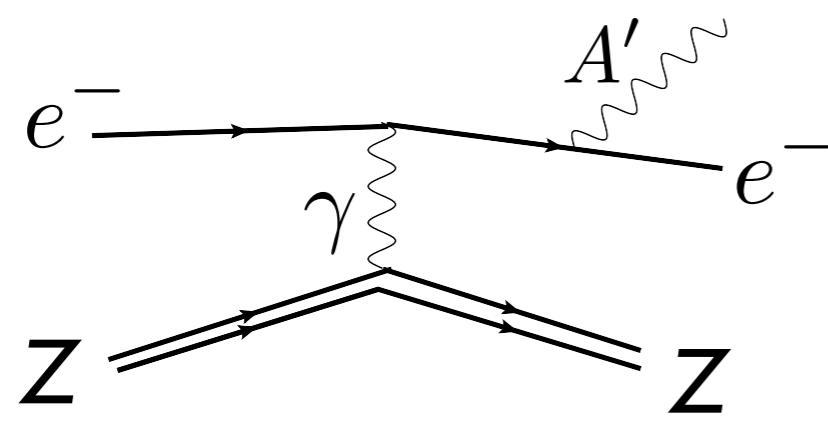
[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce  $A'$  via bremsstrahlung off  $e^-$  beam on fixed target



Target  
(e.g. tungsten)



$A'$  produced forward,  
carries most of  $E_{\text{beam}}$

$$\sigma \propto \frac{\epsilon^2 Z^2}{m_{A'}^2}$$

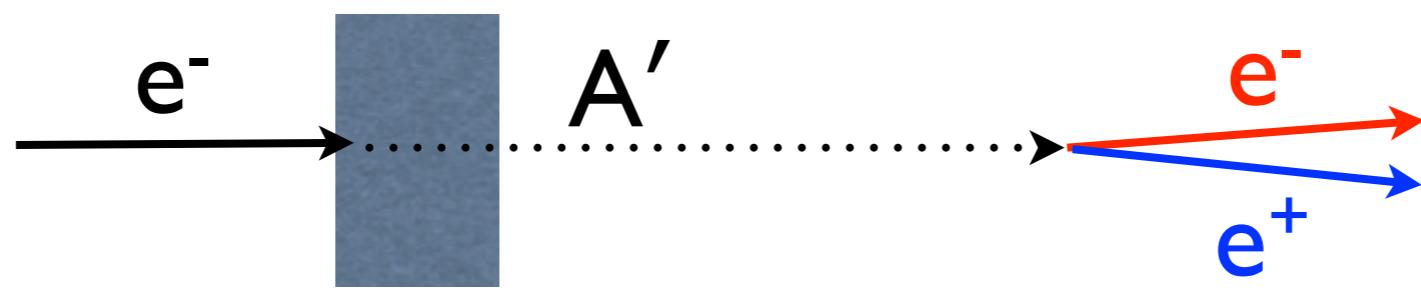
# Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

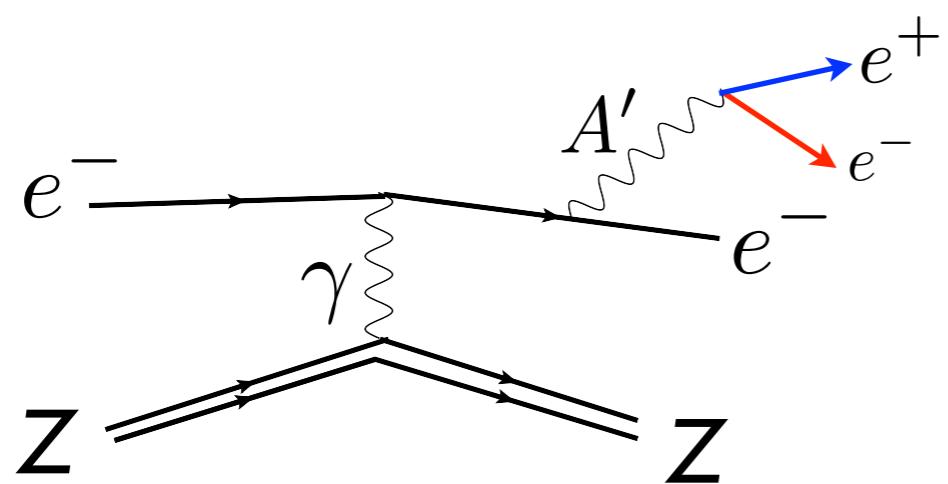
[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce  $A'$  via bremsstrahlung off  $e^-$  beam on fixed target



Target  
(e.g. tungsten)



$A'$  produced forward,  
carries most of  $E_{\text{beam}}$

assume  $A'$  decays  
to  $e^+e^-$  pair

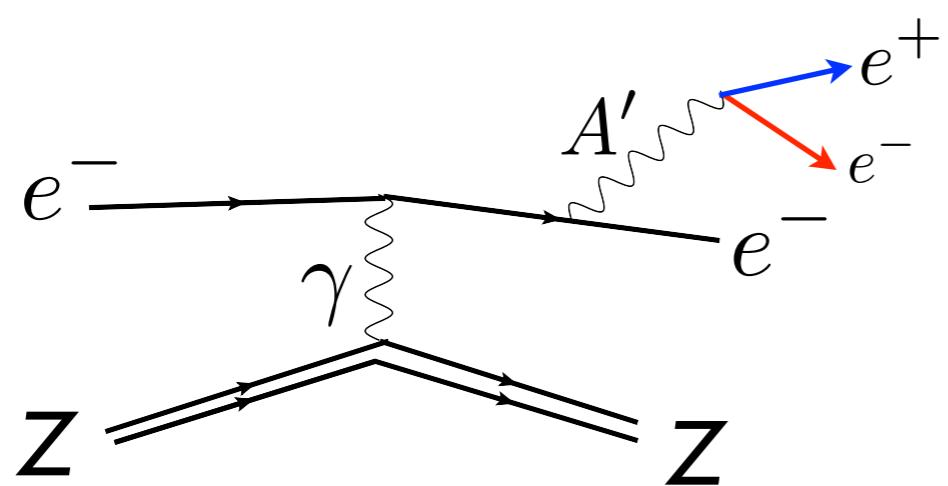
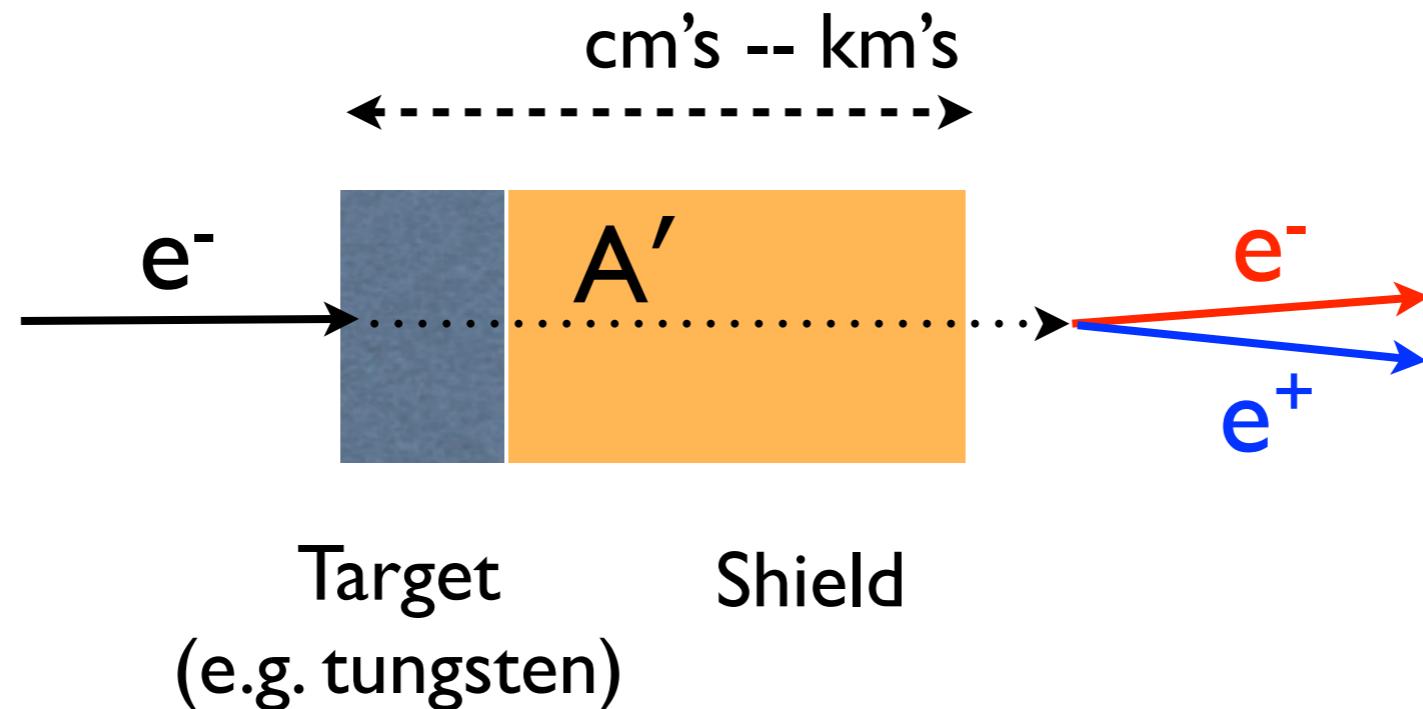
# Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce  $A'$  via bremsstrahlung off  $e^-$  beam on fixed target



$A'$  produced forward,  
carries most of  $E_{\text{beam}}$

assume  $A'$  decays  
to  $e^+e^-$  pair

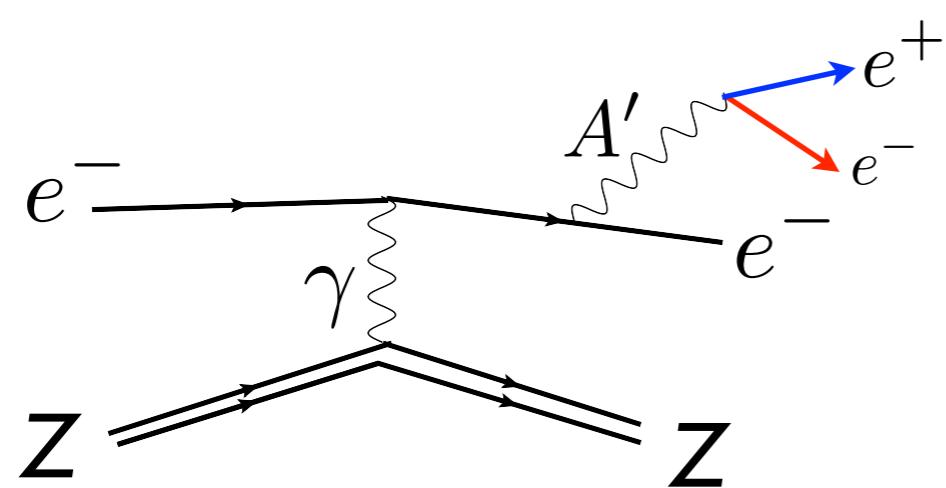
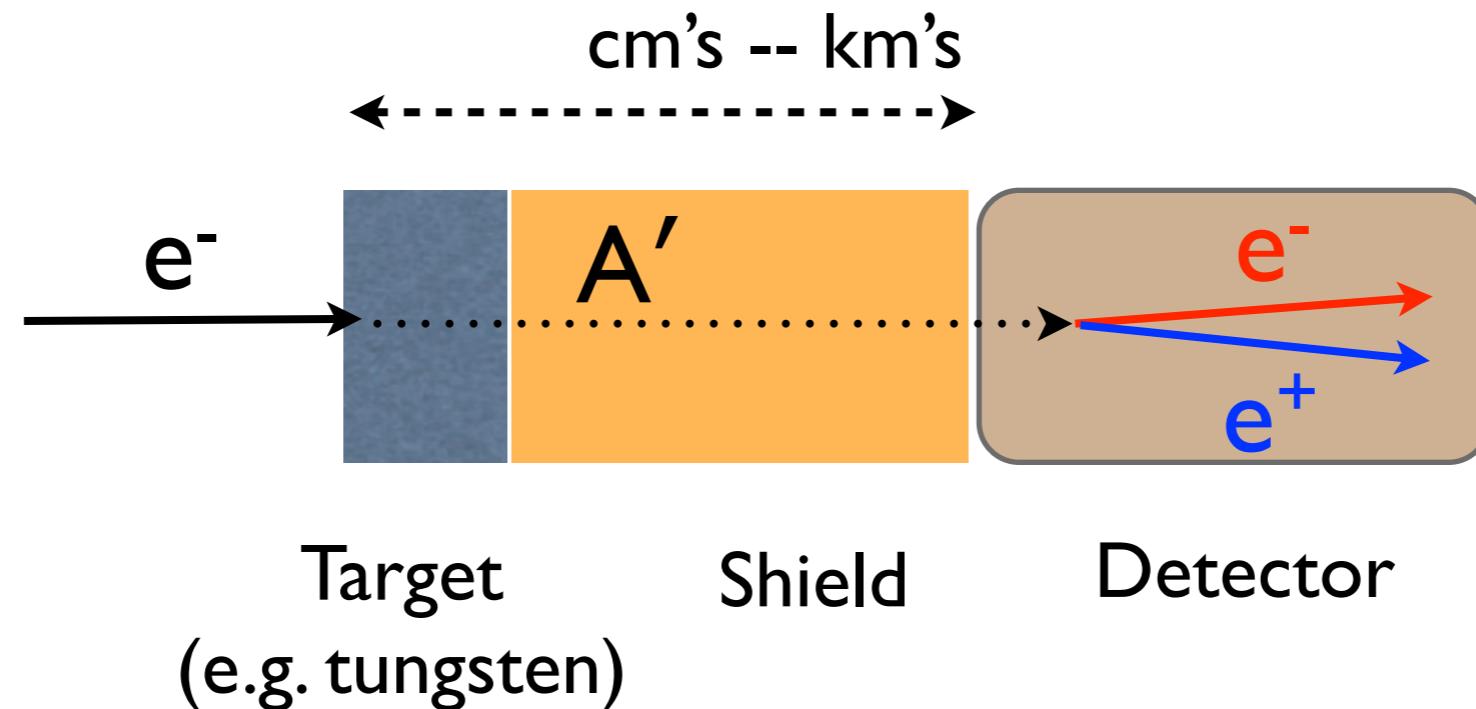
# Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce  $A'$  via bremsstrahlung off  $e^-$  beam on fixed target



$A'$  produced forward,  
carries most of  $E_{\text{beam}}$

assume  $A'$  decays  
to  $e^+e^-$  pair

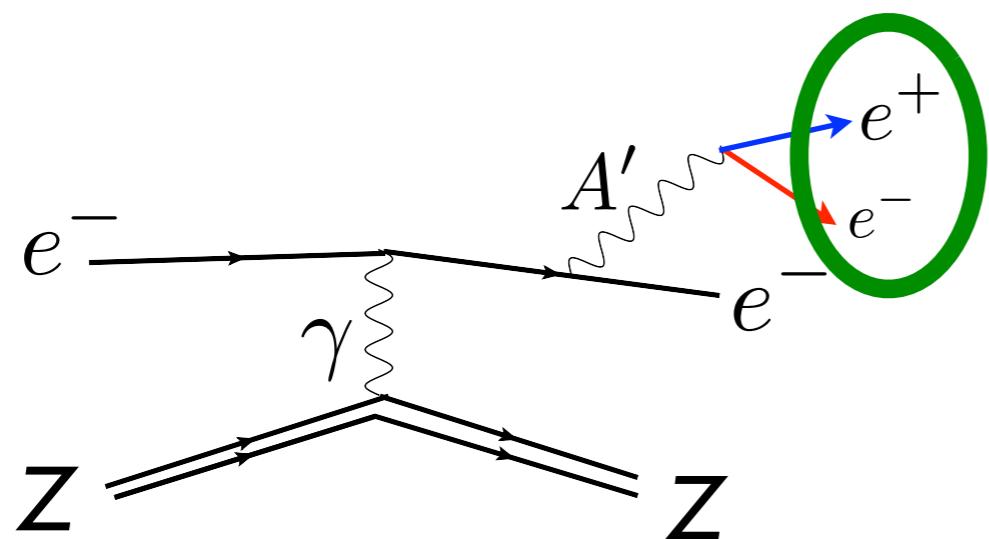
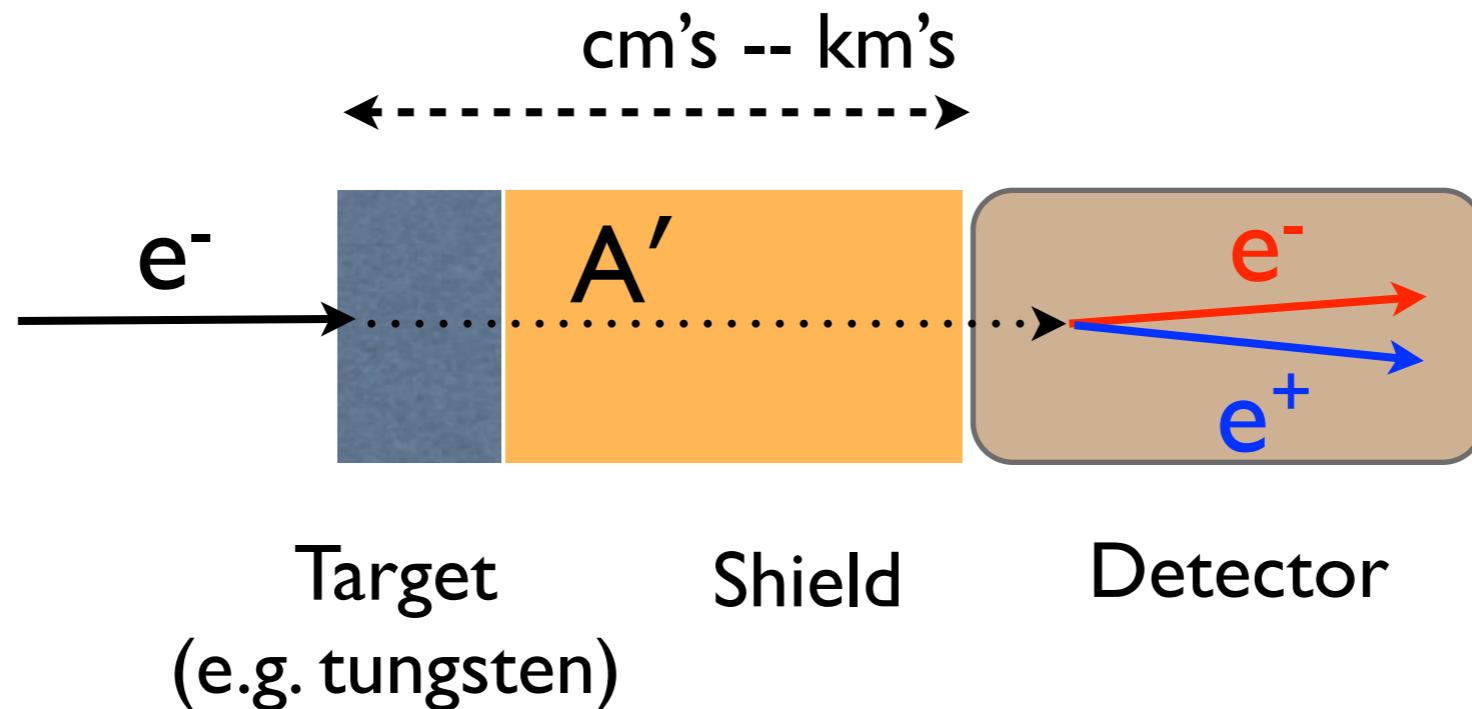
# Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce  $A'$  via bremsstrahlung off  $e^-$  beam on fixed target



invariant mass  
of  $e^+e^- = m_{A'}$

resonance helps distinguish  
signal from background

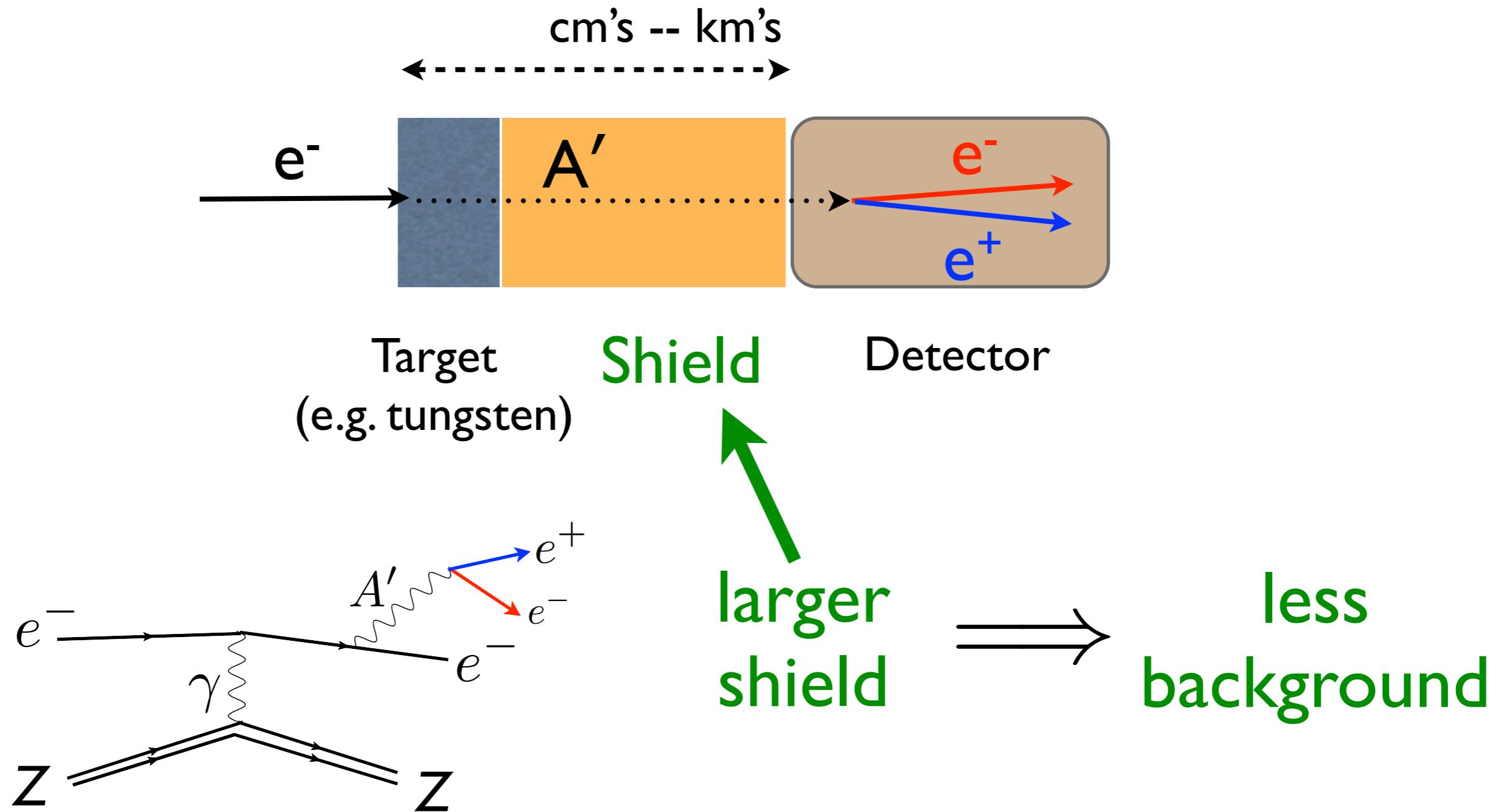
# Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

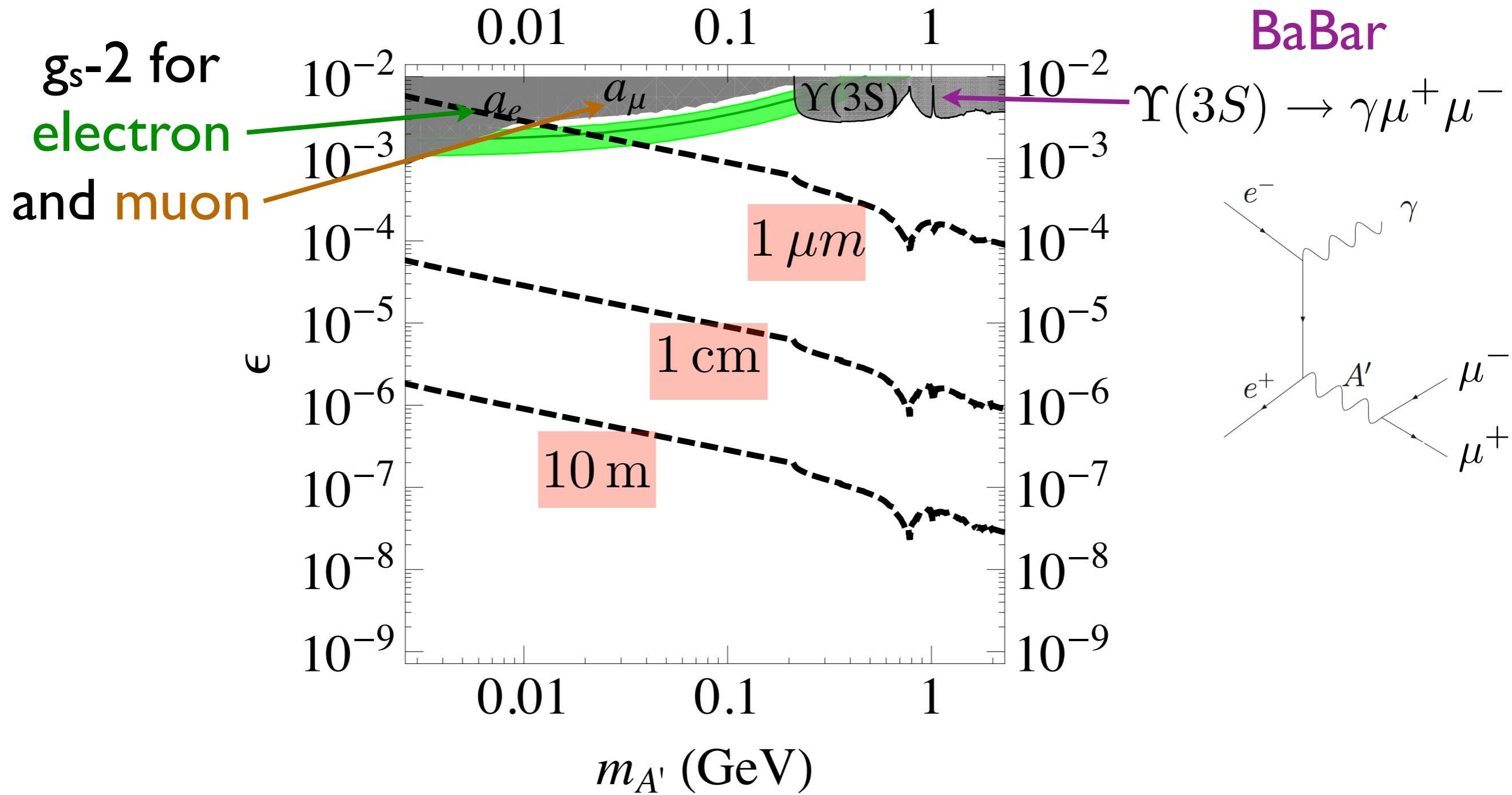
[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce  $A'$  via bremsstrahlung off  $e^-$  beam on fixed target



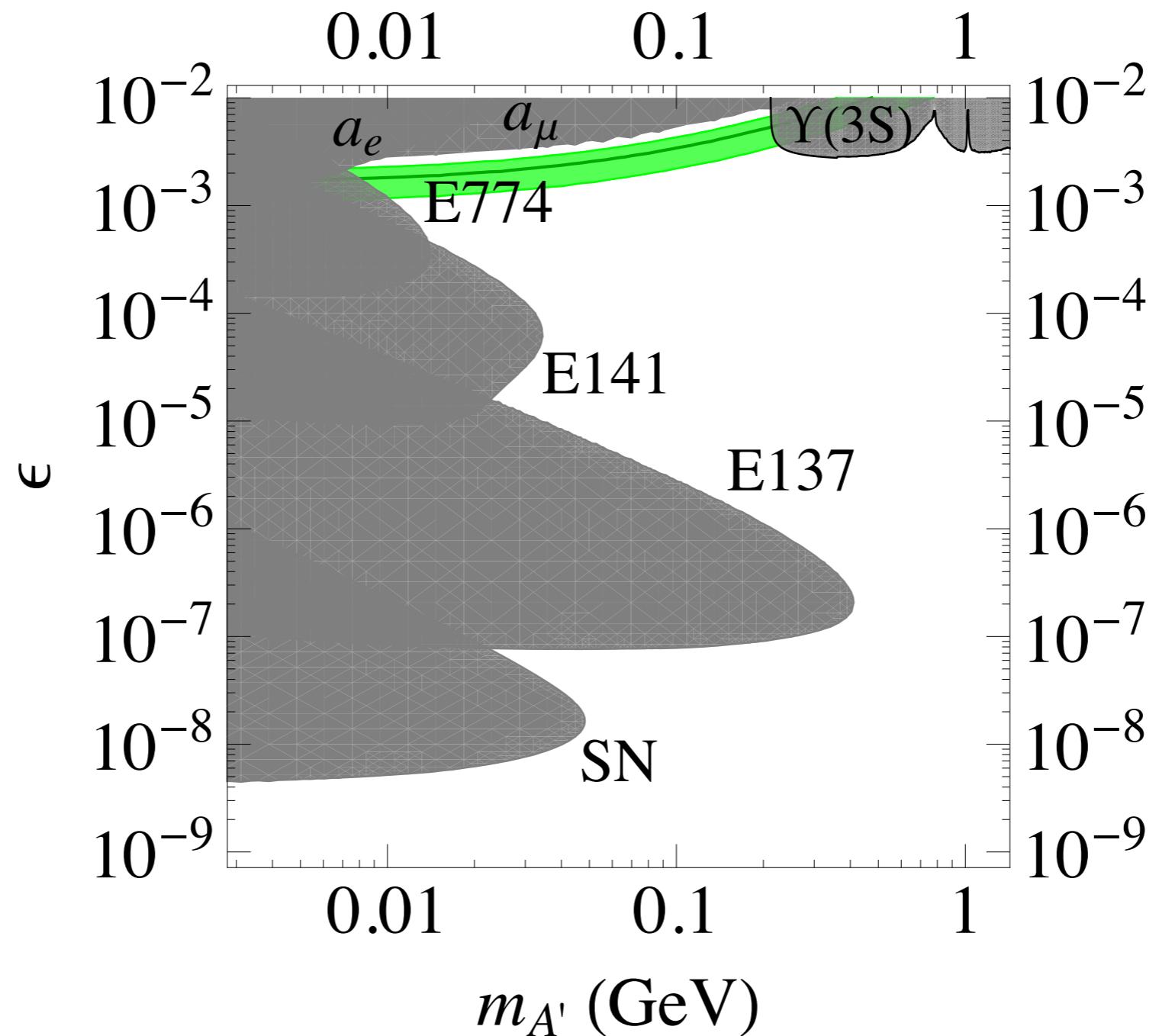
# A' lifetime varies by orders of magnitude



Need various strategies to cover whole range

# Good beam dump constraints exist

Bjorken, RE, Schuster, Toro

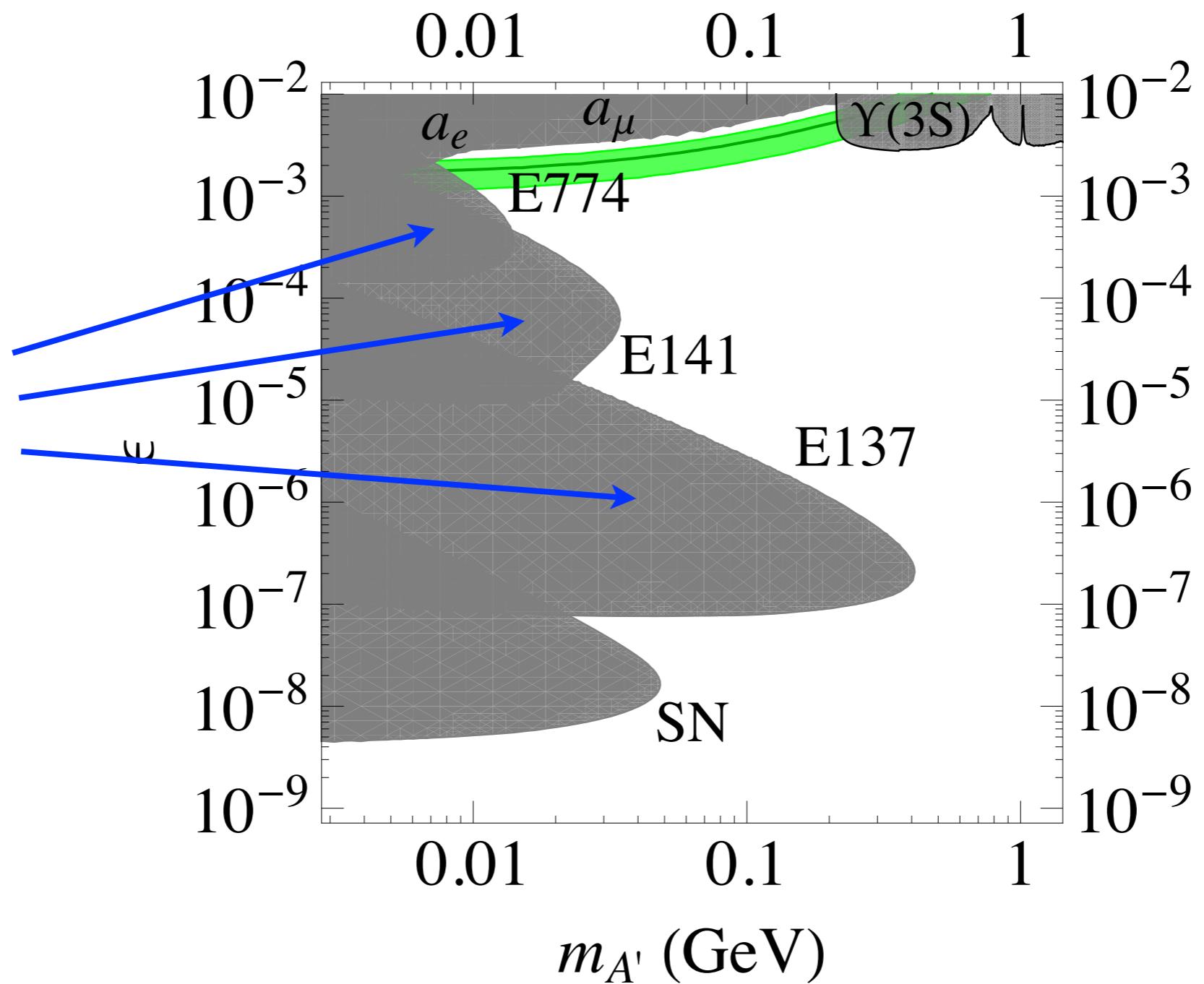


“fixed target experiments w/ large shields”

# Good beam dump constraints exist

Bjorken, RE, Schuster, Toro

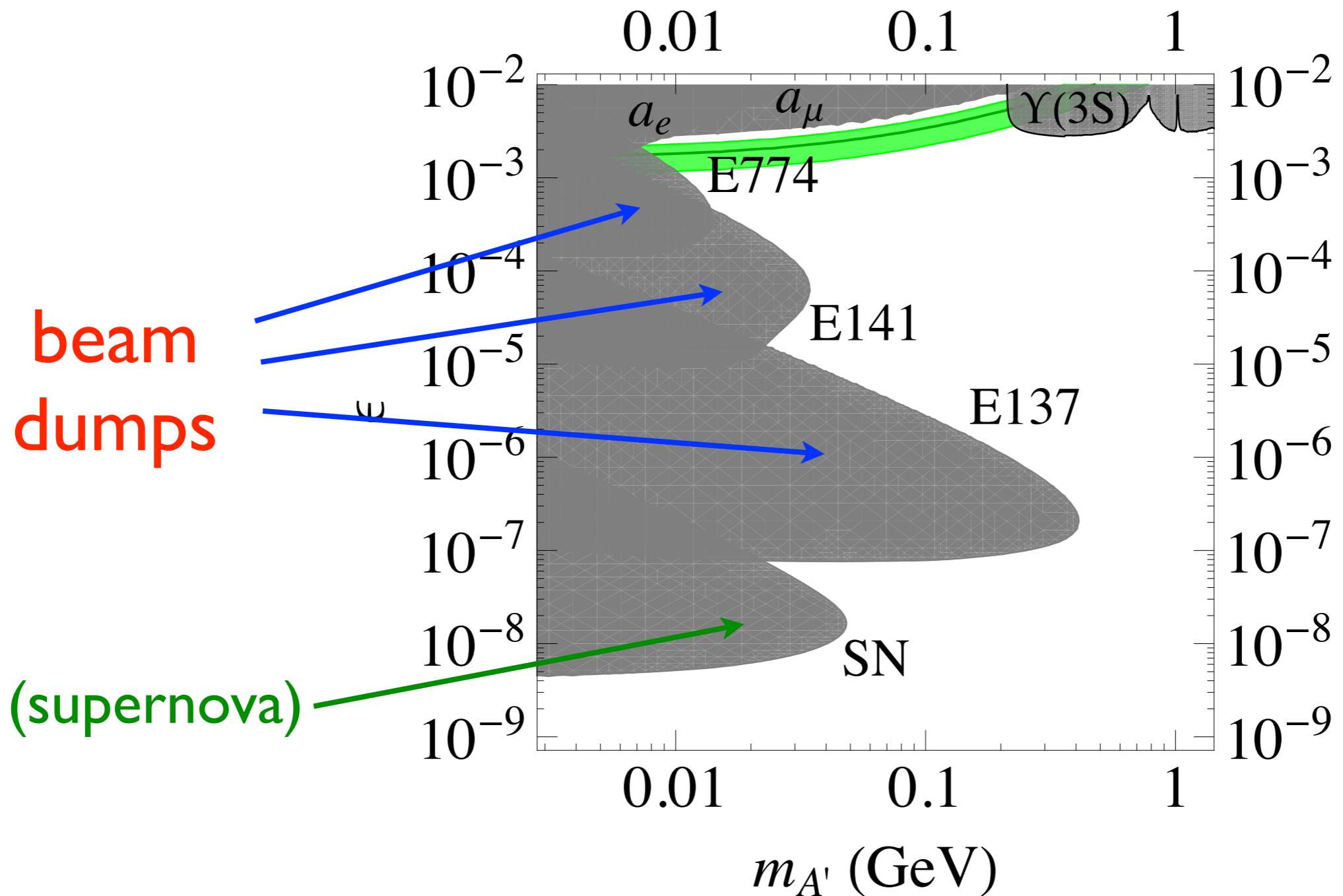
beam  
dumps



“fixed target experiments w/ large shields”

# Good beam dump constraints exist

Bjorken, RE, Schuster, Toro



“fixed target experiments w/ large shields”

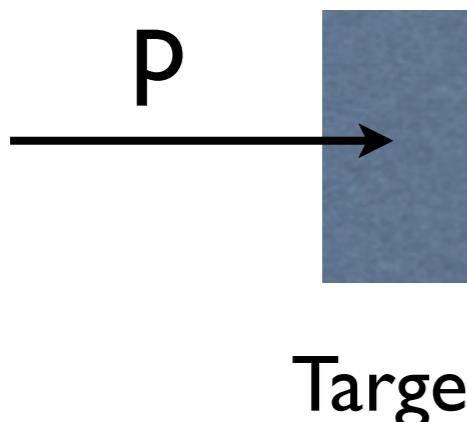
# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND, MINOS, MiniBooNE, Project X

can produce  $A'$  from meson decays



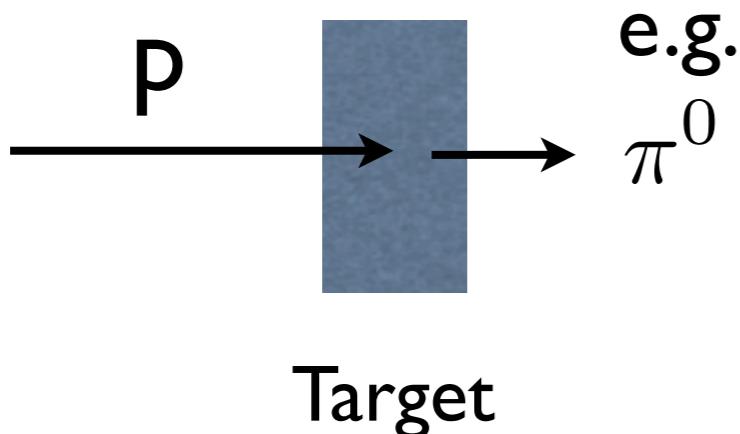
# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND, MINOS, MiniBooNE, Project X

can produce A' from meson decays



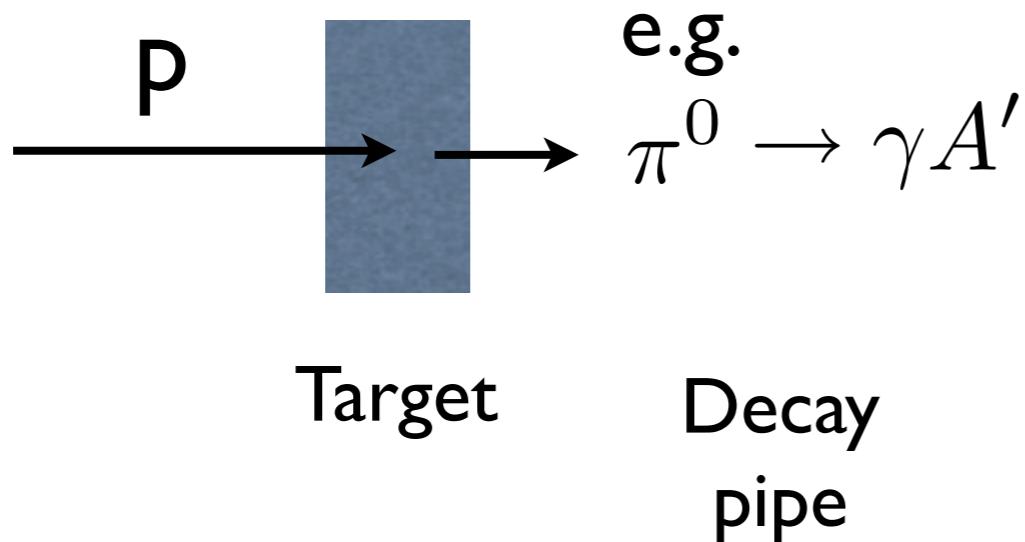
# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND, MINOS, MiniBooNE, Project X

can produce  $A'$  from meson decays



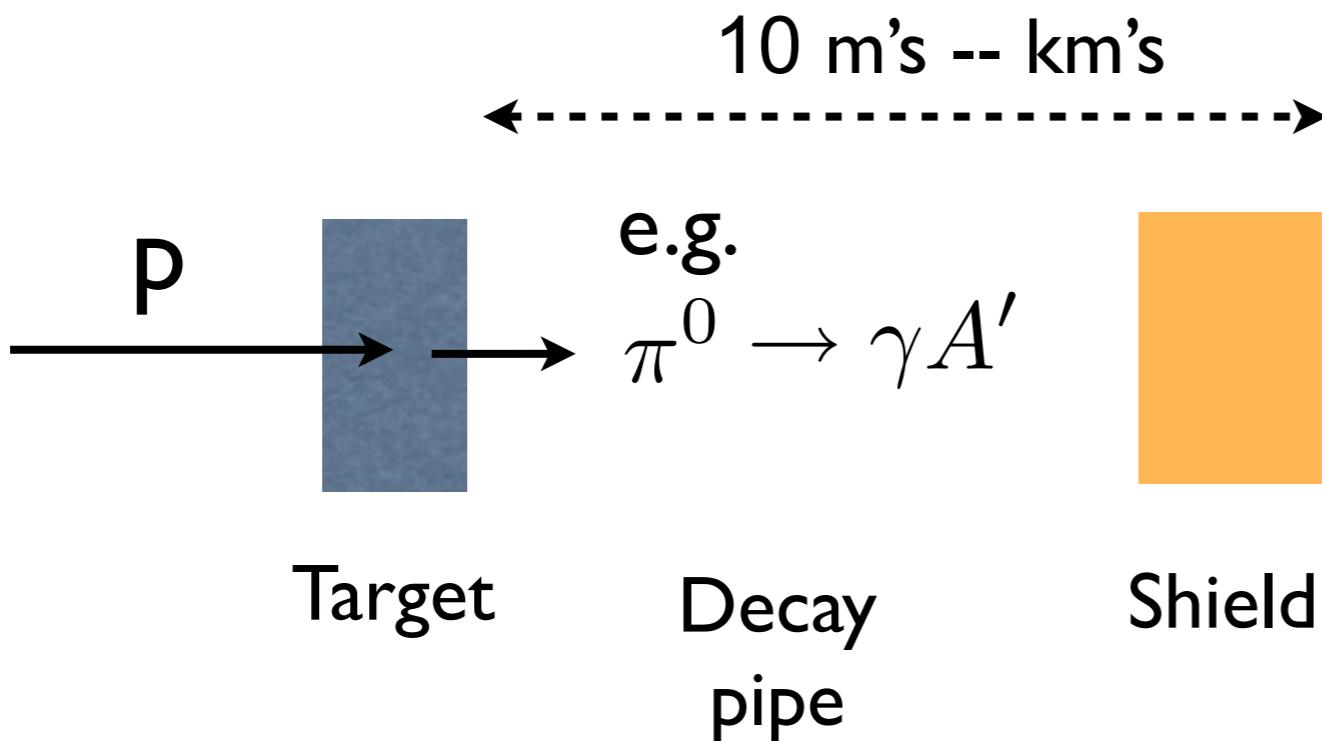
# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND, MINOS, MiniBooNE, Project X

can produce  $A'$  from meson decays



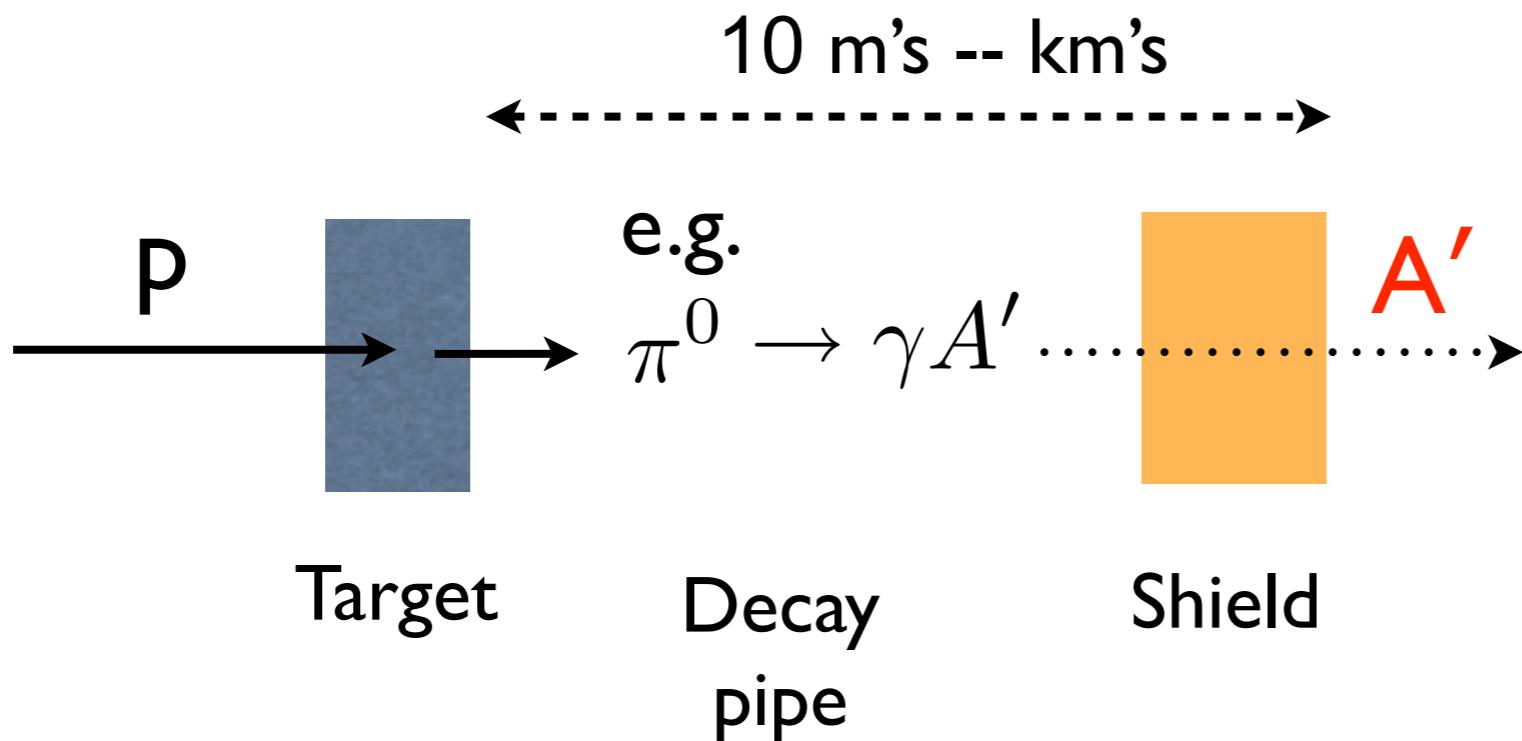
# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND, MINOS, MiniBooNE, Project X

can produce  $A'$  from meson decays



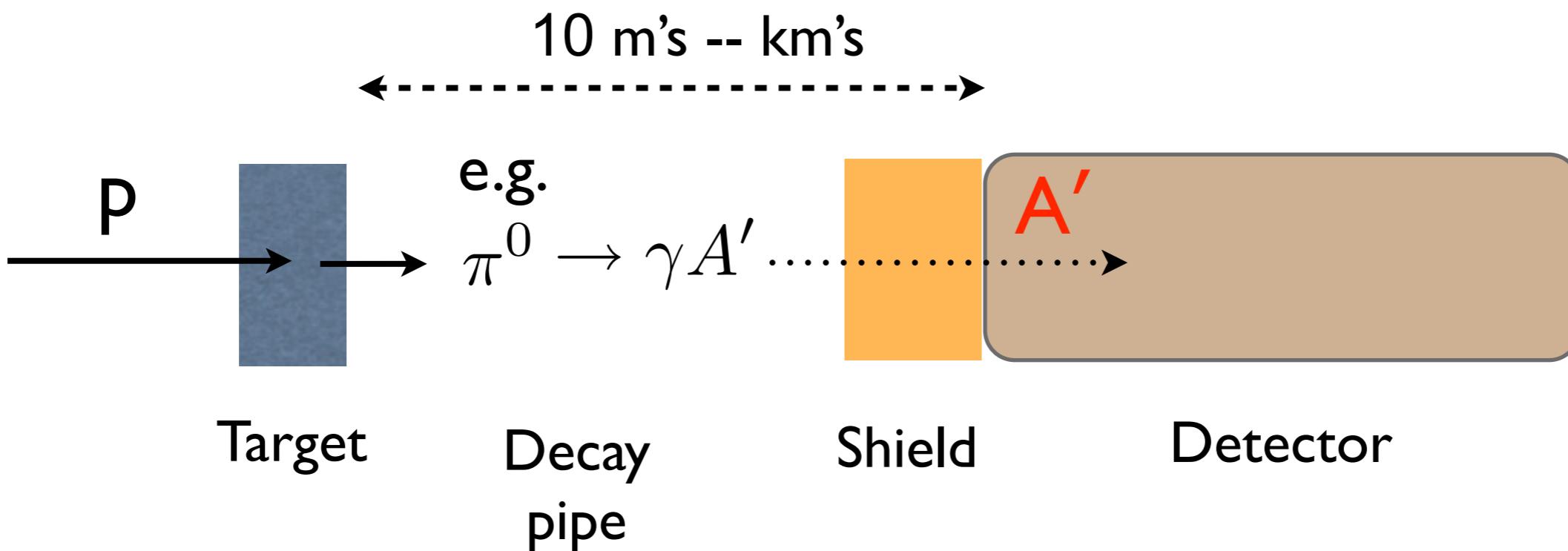
# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND, MINOS, MiniBooNE, Project X

can produce  $A'$  from meson decays



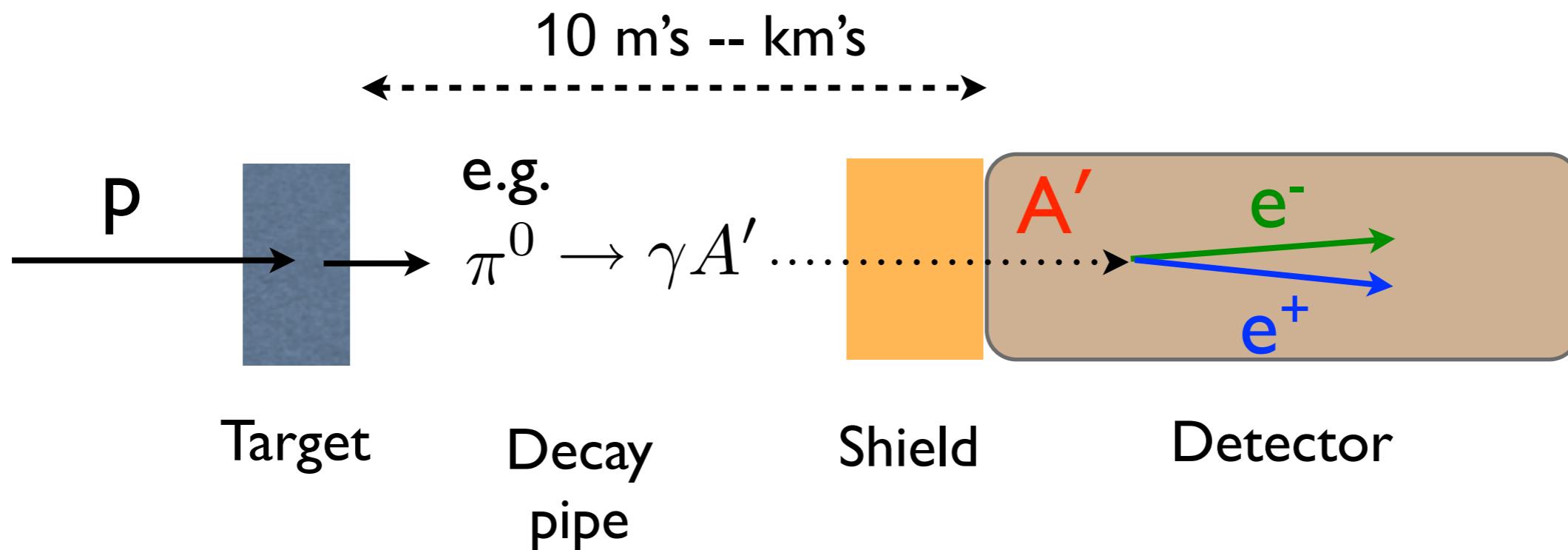
# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND, MINOS, MiniBooNE, Project X

can produce  $A'$  from meson decays



# Proton-beam fixed target experiments

Experiment	$N_{\text{POT}}$	Energy	$d$
CHARM	$10^{18}$	400 GeV	480 m
LSND	$10^{23}$	800 MeV	30 m
MiniBooNE	$10^{21}$	9 GeV	540 m
NuMI/MINOS	$10^{20}$	120 GeV	1 km

↑  
protons on  
target

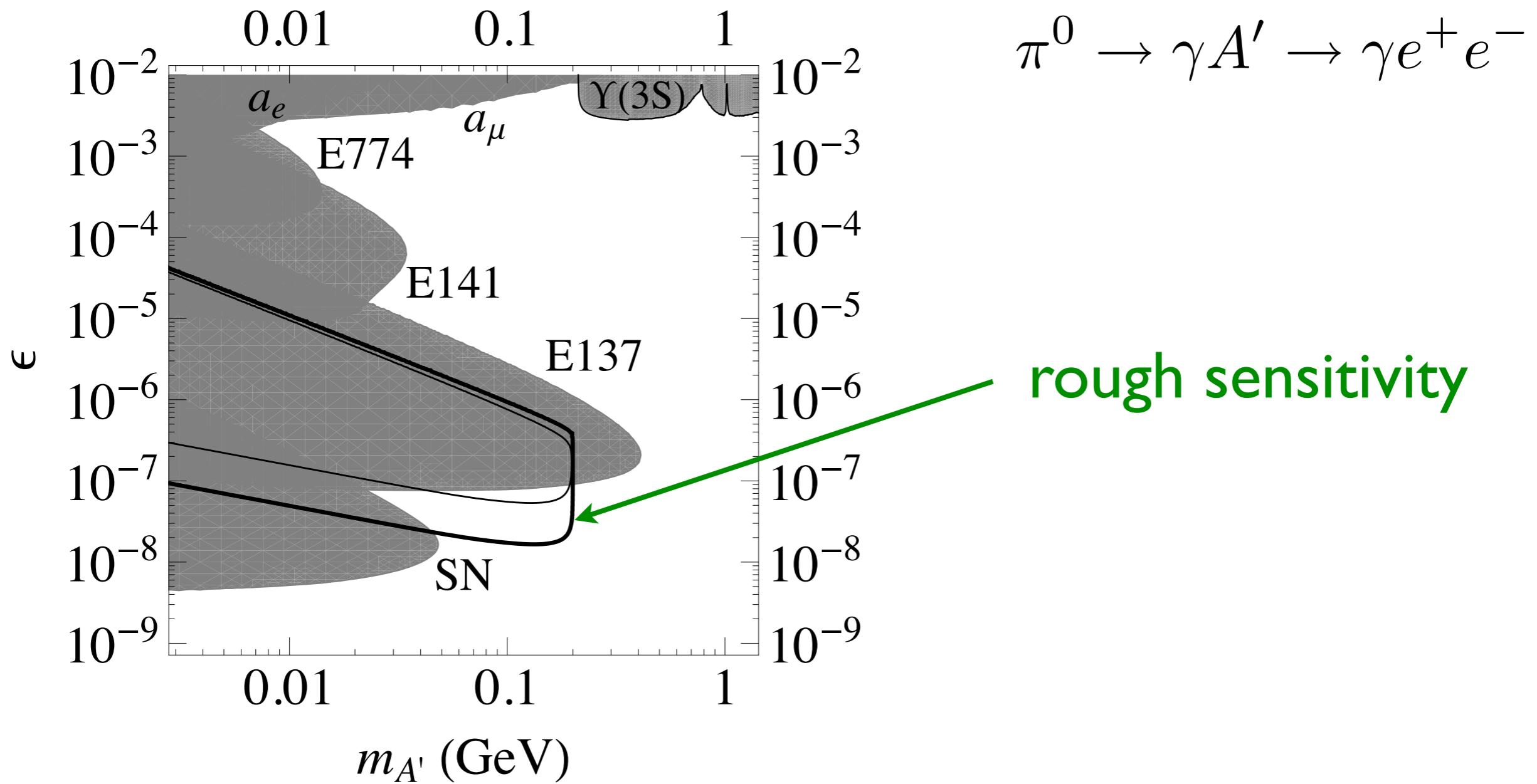
(Batell)

# Proton-beam fixed target experiments

[Batell, Pospelov, Ritz]

[RE, Harnik, Kaplan, Toro]

e.g. LSND dumped  $\sim 10^{23}$  protons, producing  $\sim 10^{22}$  pions



# Proton-beam fixed target experiments

More generally, many interesting  
searches could be done !  
(no time to discuss)

some exciting possibilities for  
MINOS, MiniBooNE, + Project X

includes searches for more complicated hidden  
sectors, axion-like particles, MeV-mass dark matter...

local contacts: Roni Harnik (FNAL), Brian Batell (Chicago)

# Proton-beam fixed target experiments

More generally, many interesting  
searches could be done !  
(no time to discuss)

some exciting possibilities for  
MINOS, MiniBooNE, + Project X

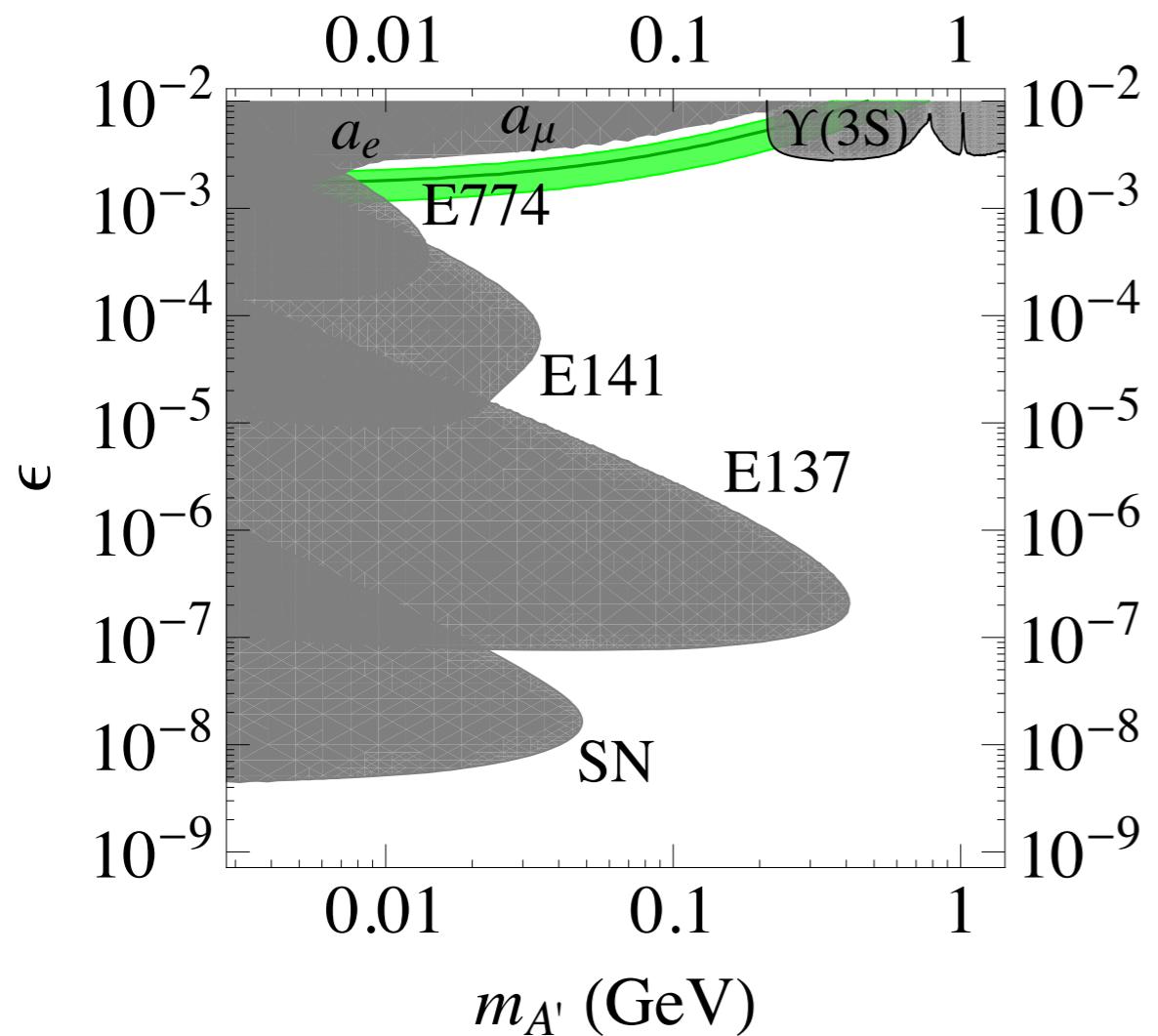
includes searches for more complicated hidden  
sectors, axion-like particles, MeV-mass dark matter...

local contacts: Roni Harnik (FNAL), Brian Batell (Chicago)

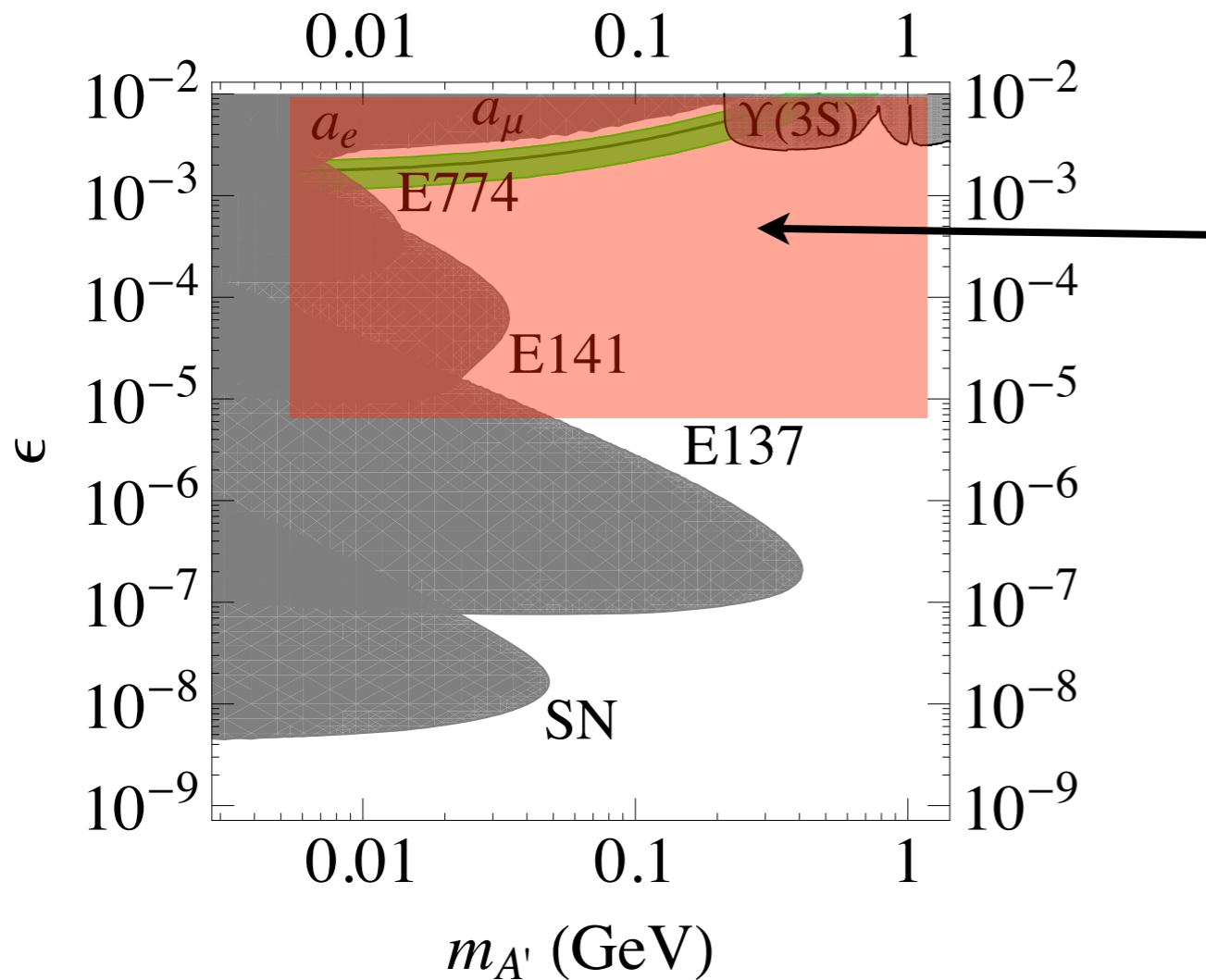
focus now again on *electron* fixed target experiments

# Need new experiments

Bjorken, RE, Schuster, Toro



# Need new experiments

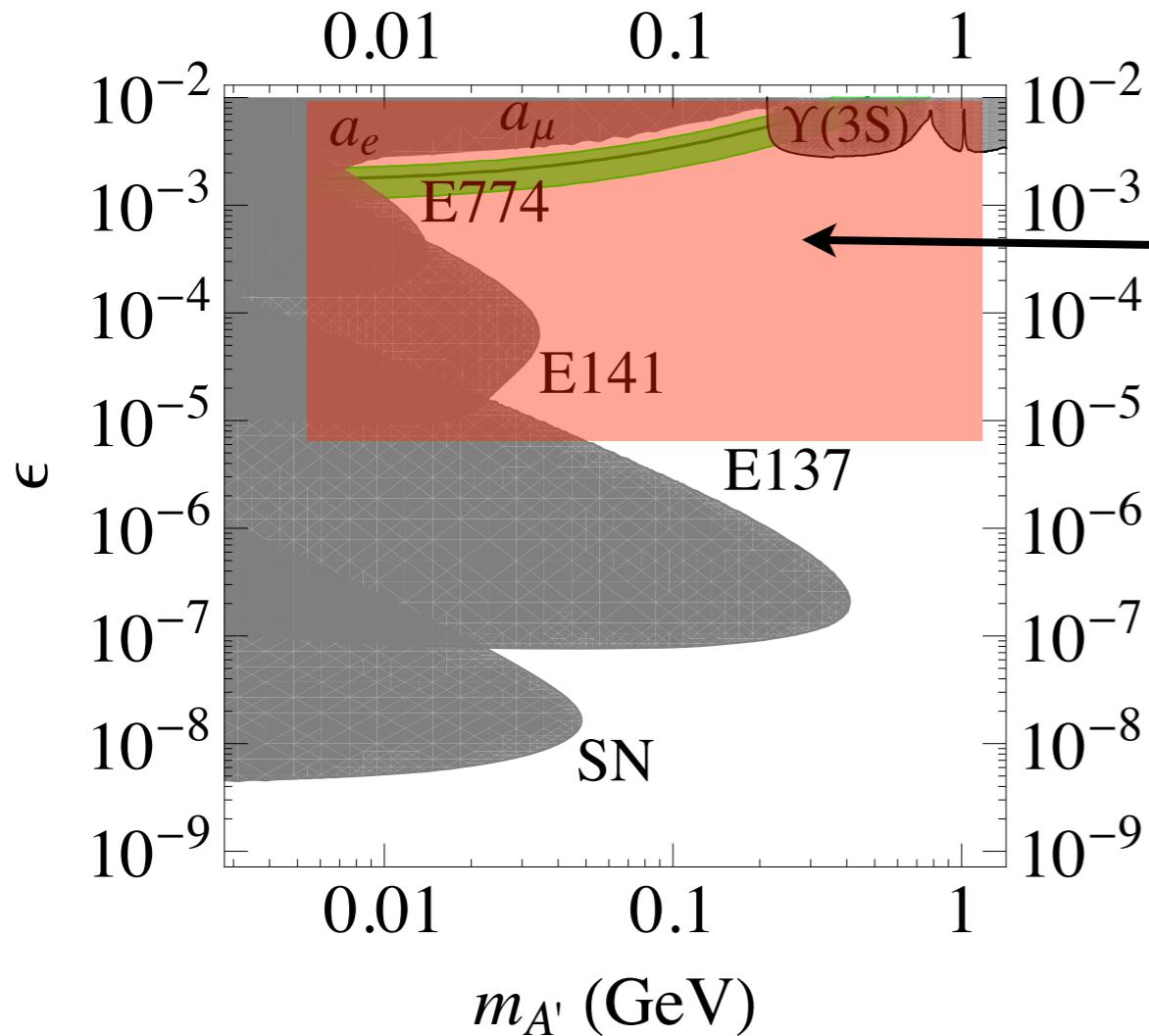


Bjorken, RE, Schuster, Toro

Interesting unexplored region

A' lifetime short,  
so need *thin* target

# Need new experiments

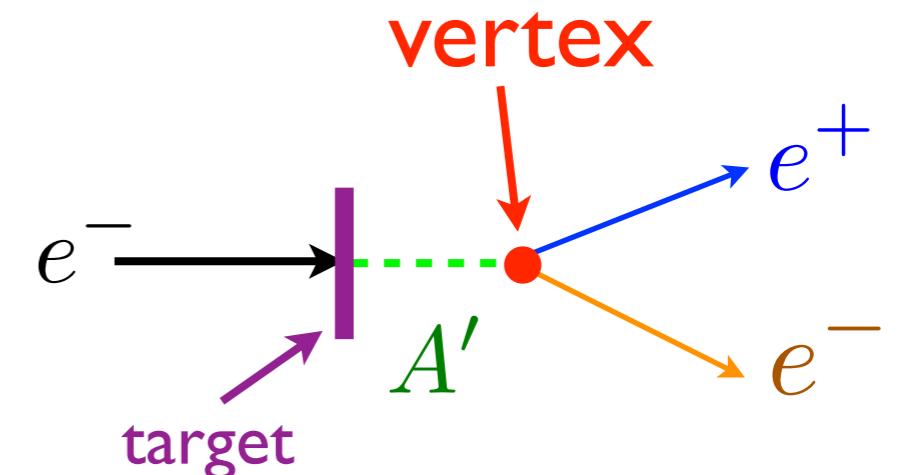
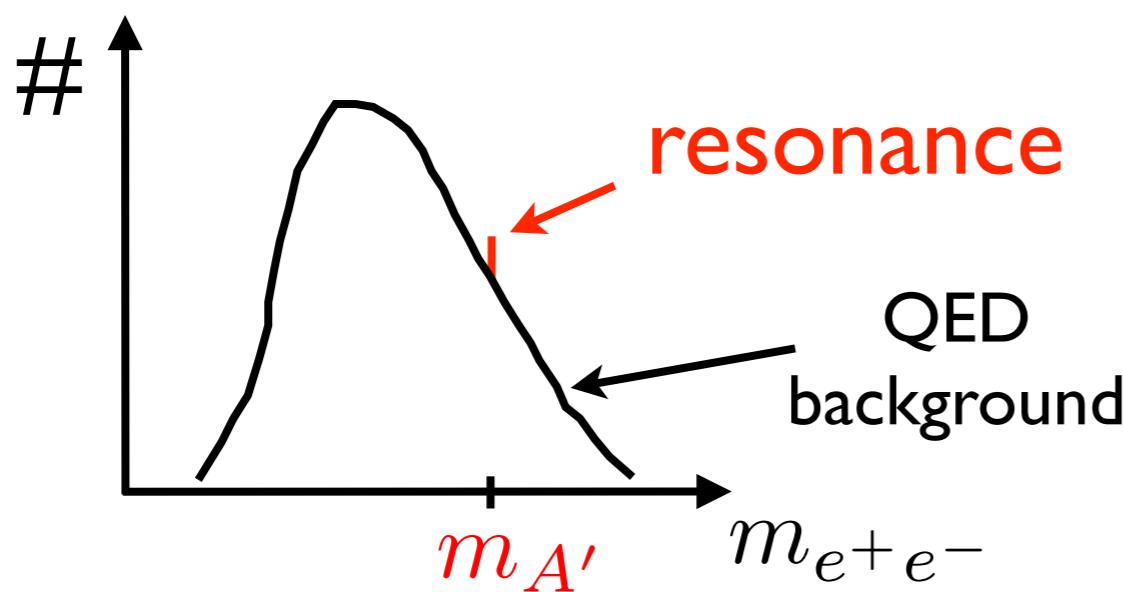


Bjorken, RE, Schuster, Toro

Interesting  
unexplored region

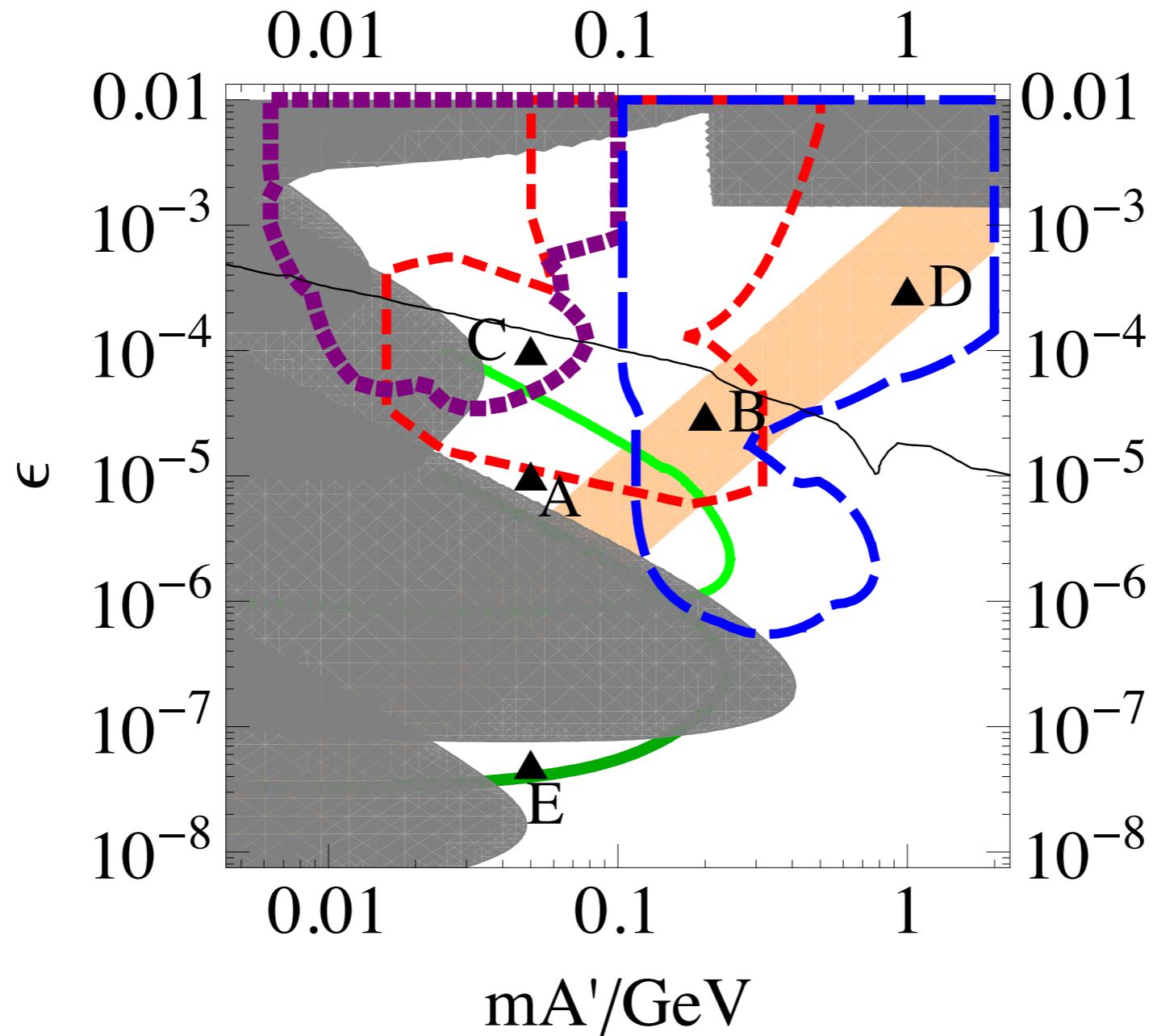
$A'$  lifetime short,  
so need *thin* target

Large background, but:  
look for resonance or vertex



# A new experimental search program

Bjorken, RE, Schuster, Toro



June 2009

several real proposals developed since June 2009

# Current & Planned Experiments

- JLab      {
  - A' Experiment (APEX)
  - Heavy Photon Search (HPS)
  - DarkLight
- Germany    • MAMI in Mainz
- Russia     • VEPP-3

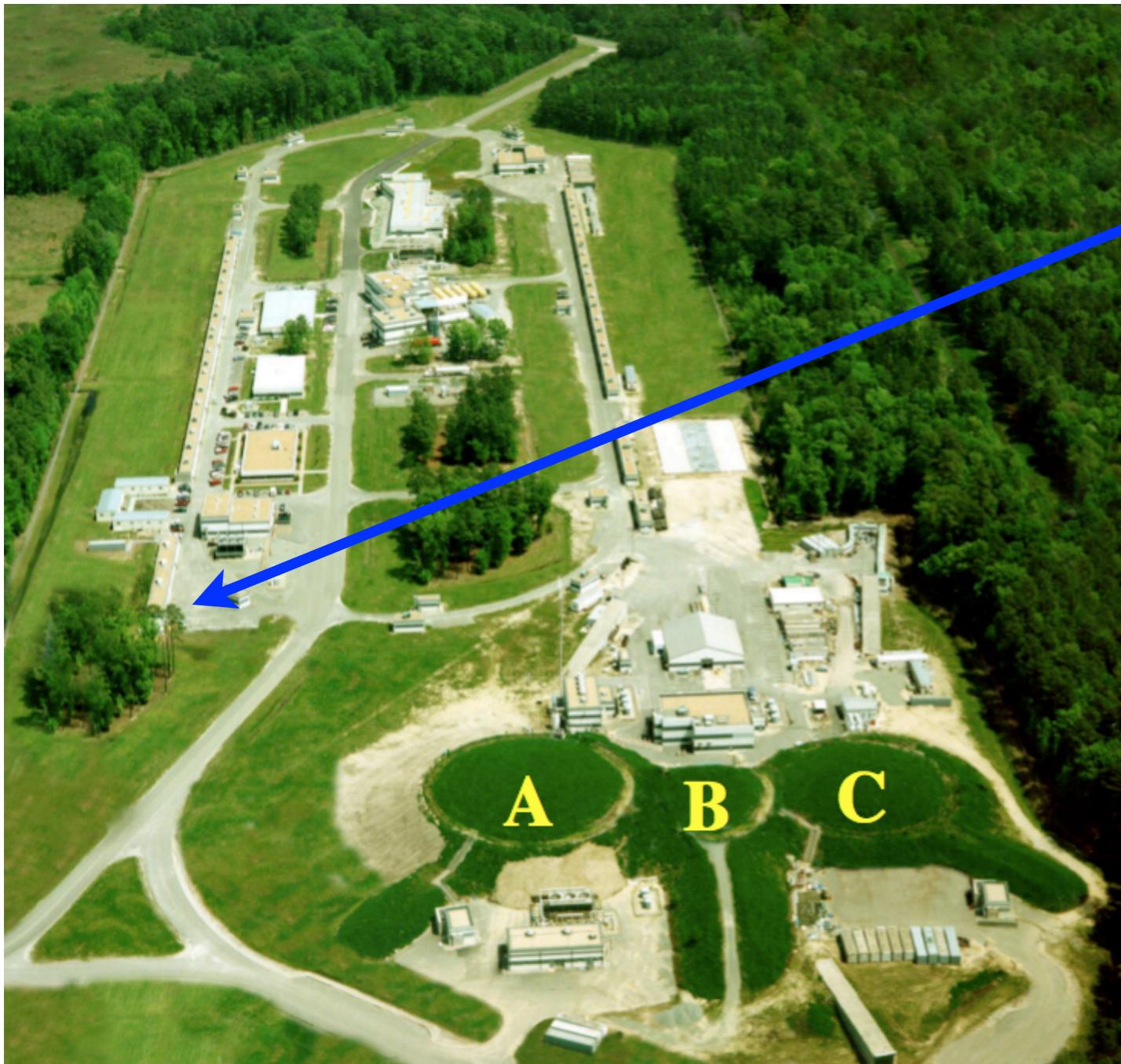
# The A' Experiment (**APEX**) @JLAB Hall A

S. Abrahamyan, A. Afanasev, Z. Ahmed, E. Aliotta, K. Allada, D. Anez, D. Armstrong, T. Averett, A. Barbieri, K. Bartlett, J. Beacham, S. Beck, J. D. Bjorken, J. Bono, P. Bosted, J. Boyce, P. Brindza, N. Bubis, A. Camsonne, O. Chen, K. Cranmer, C. Curtis, E. Chudakov, M. Dalton, C. W. de Jager, A. Deur, J. Donaghy, **R. Essig (co-spokesperson)**, C. Field, E. Folts, A. Gasparian, A. Gavalya, S. Gilad, R. Gilman, A. Glamazdin, N. Goeckner-Wald, J. Gomez, M. Graham, O. Hansen, D. W. Higinbotham, T. Holmstrom, J. Huang, S. Iqbal, J. Jaros, E. Jensen, A. Kelleher, M. Khandaker, I. Korover, G. Kumbartzki, J. J. LeRose, R. Lindgren, N. Liyanage, E. Long, J. Mammei, P. Markowitz, T. Maruyama, V. Maxwell, J. McDonald, D. Meekins, R. Michaels, M. Mihovilović, K. Moffeit, S. Nanda, V. Nelyubin, B. E. Norum, A. Odian, M. Oriunno, R. Partridge, M. Paolone, E. Piasetzky, I. Pomerantz, A. Puckett, V. Punjabi, Y. Qiang, R. Ransome, S. Riordan, Y. Roblin, G. Ron, K. Saenboonruang, A. Saha, B. Sawatzky, **P. Schuster (co-spokesperson)**, J. Segal, L. Selvy, A. Shahinyan, R. Shneor, S. Širca, R. Subedi, V. Sulkosky, S. Stepanyan, **N. Toro (co-spokesperson)**, D. Waltz, L. Weinstein, **B. Wojtsekhowski (co-spokesperson)**, J. Zhang, Y. Zhang, B. Zhao,  
**and The Hall A Collaboration**

# JLab's Continuous Electron Beam Accelerator Facility

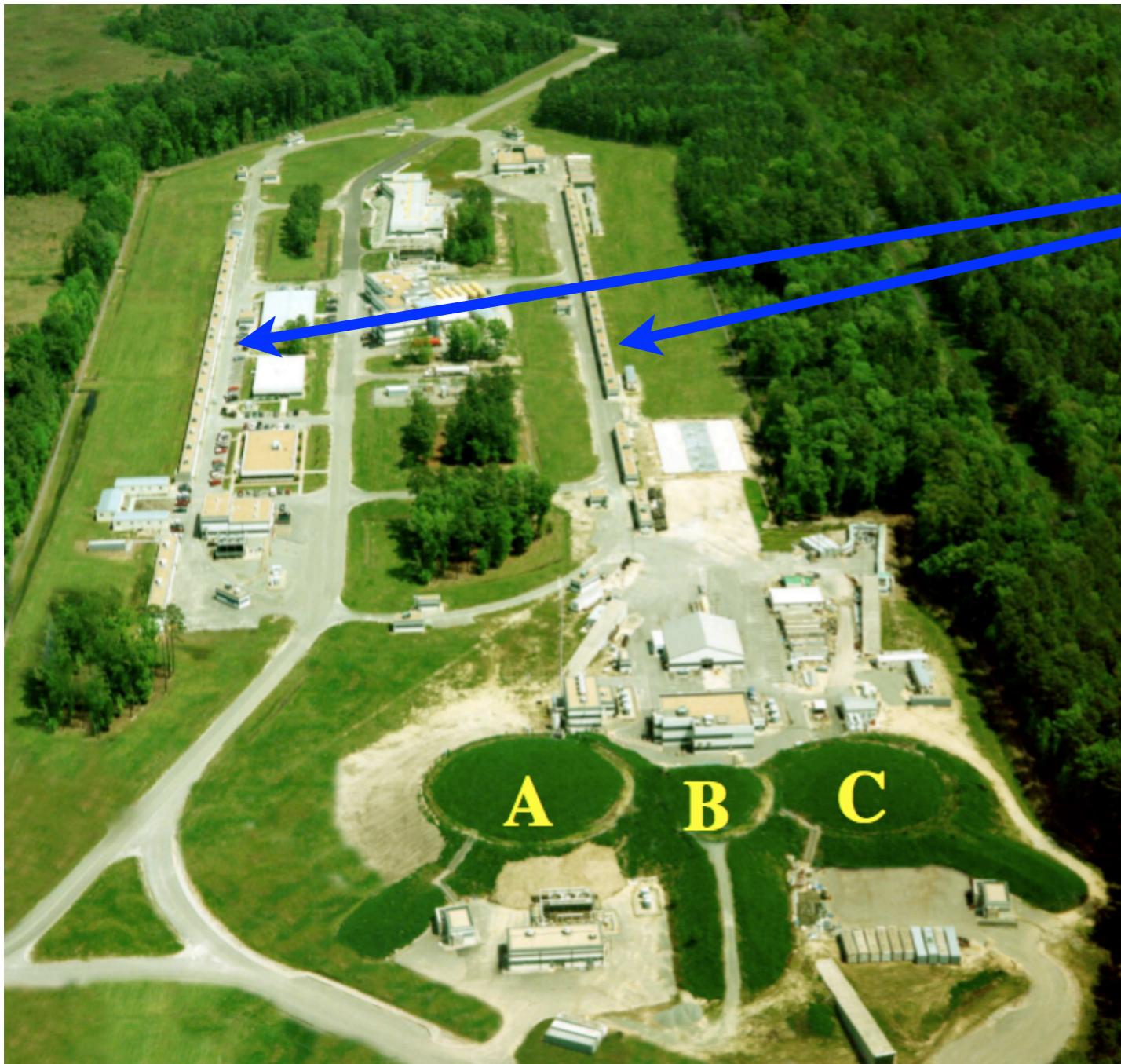


# JLab's Continuous Electron Beam Accelerator Facility



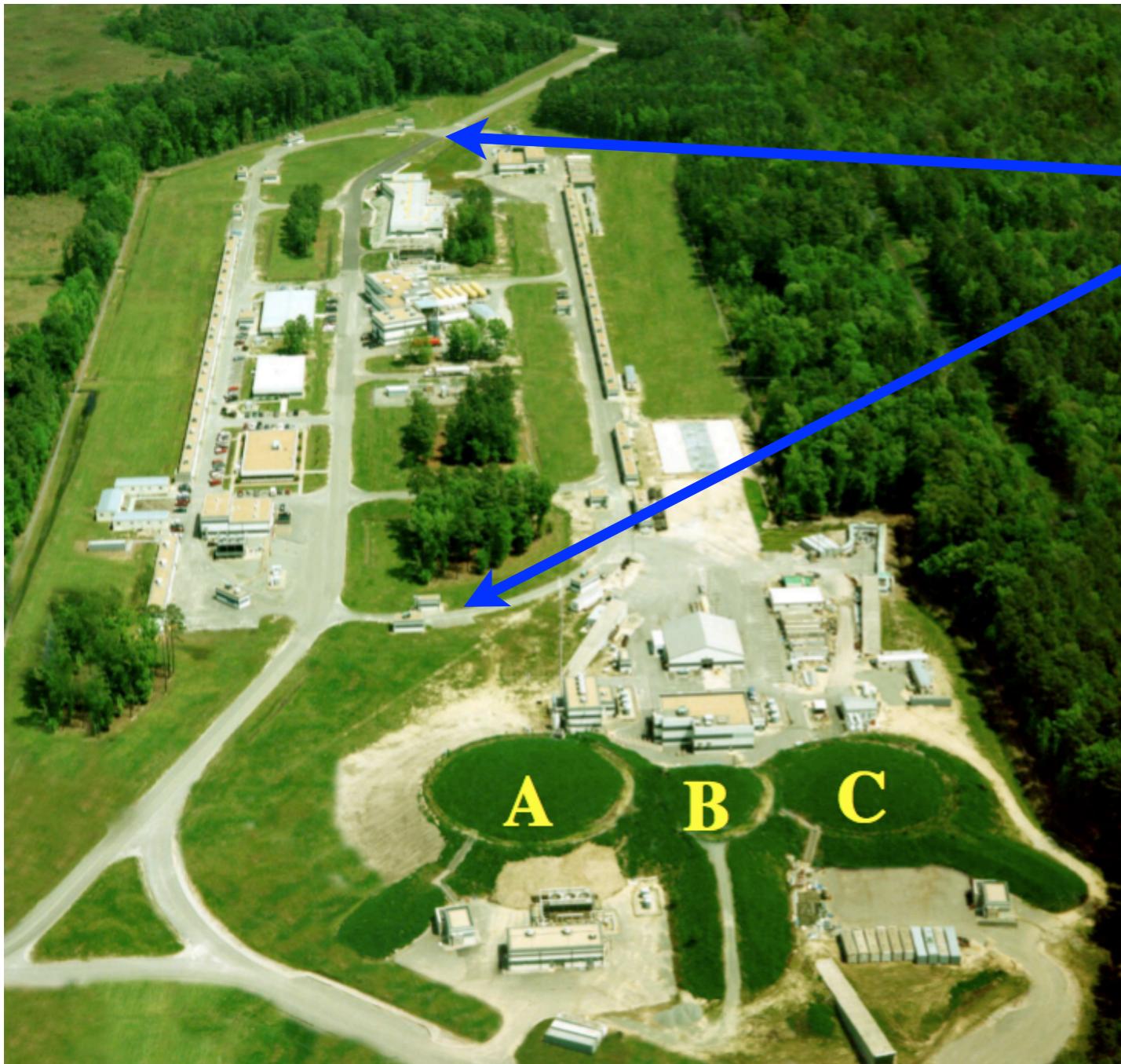
injector

# JLab's Continuous Electron Beam Accelerator Facility



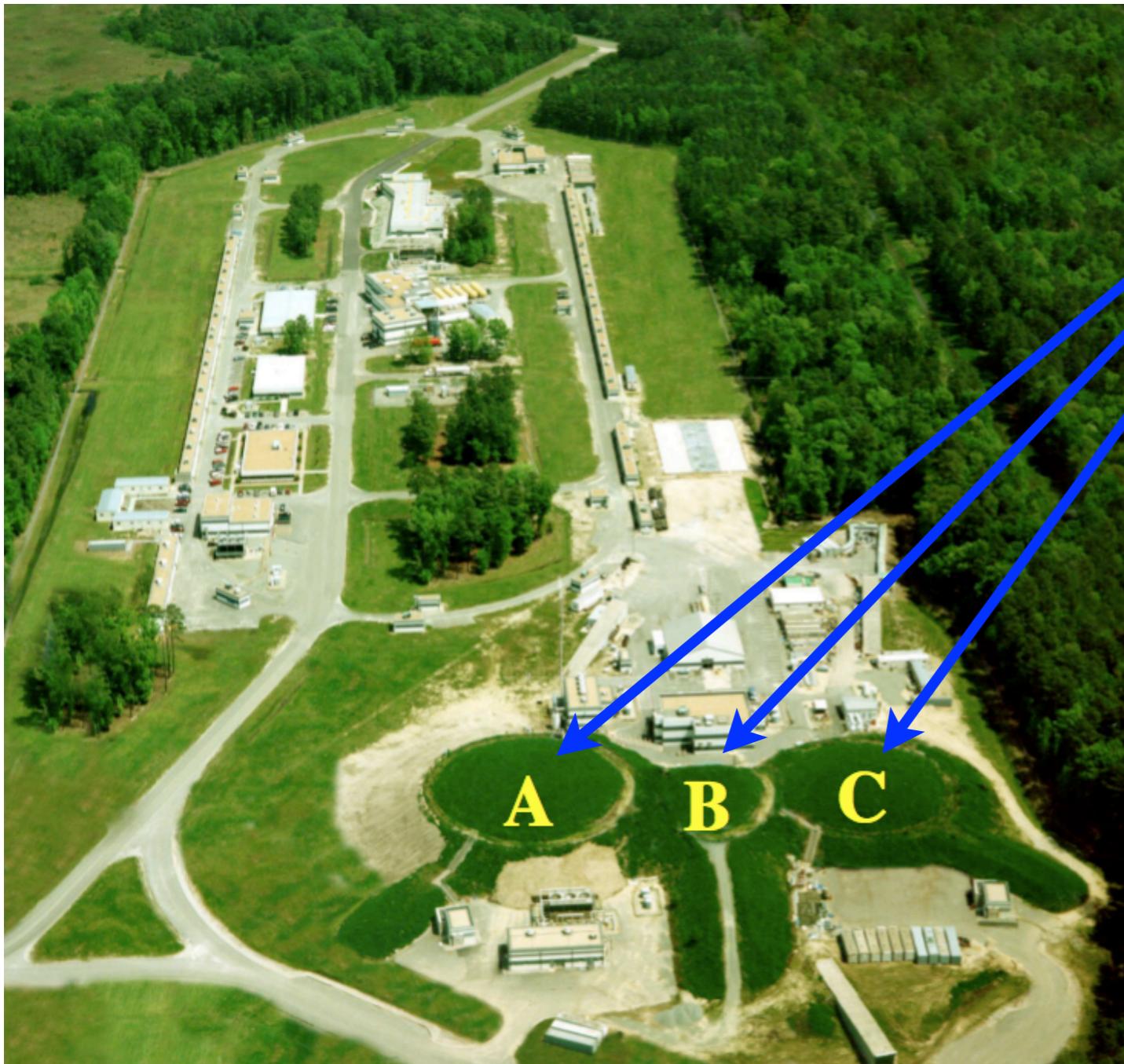
accelerating  
structures

# JLab's Continuous Electron Beam Accelerator Facility



recirculating  
arcs

# JLab's Continuous Electron Beam Accelerator Facility



Experimental  
Halls

# JLab's Continuous Electron Beam Accelerator Facility



$E_{beam} \sim 1.1 - 5.5 \text{ GeV}$

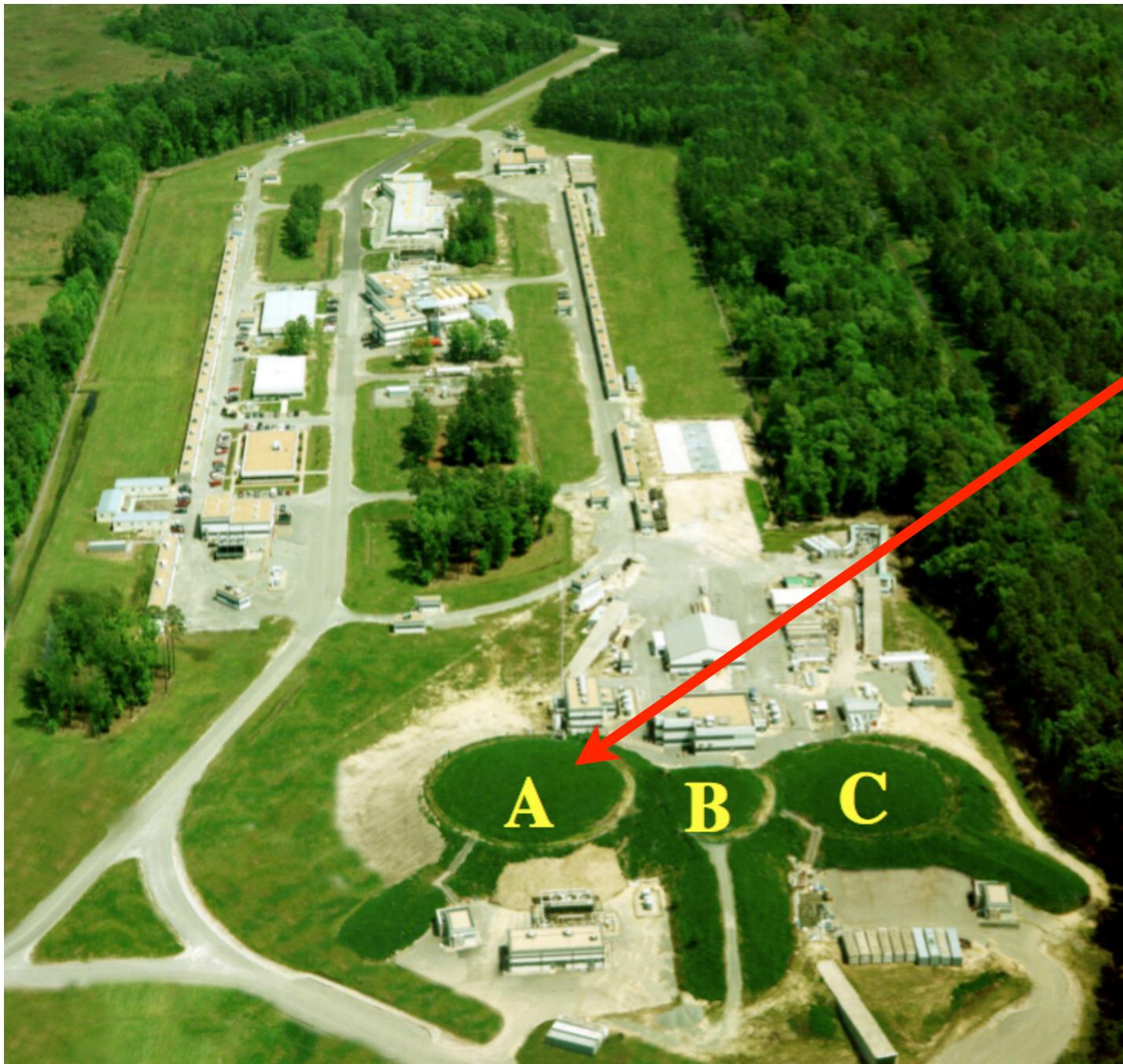
$I_{beam} < 200 \mu\text{A}$  (A&C)

$< 700 \text{ nA}$  (B)

after upgrade  
(~2012-2014)

$E_{beam} \sim 2.2 - 11 \text{ GeV}$

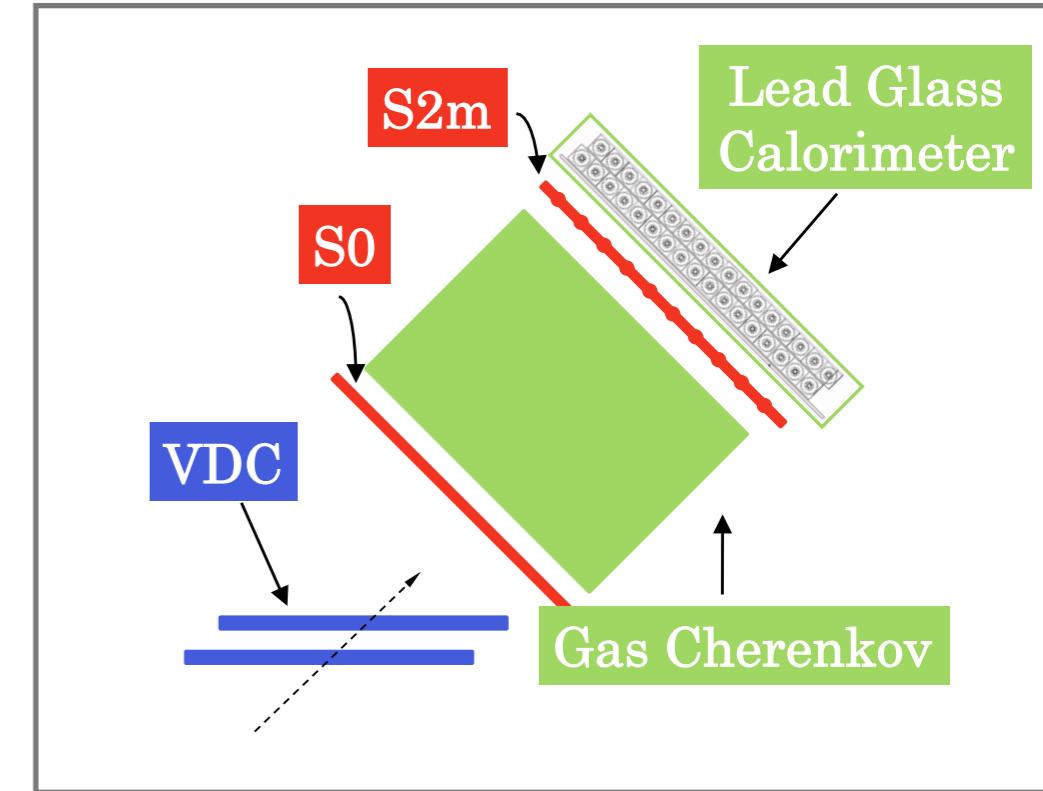
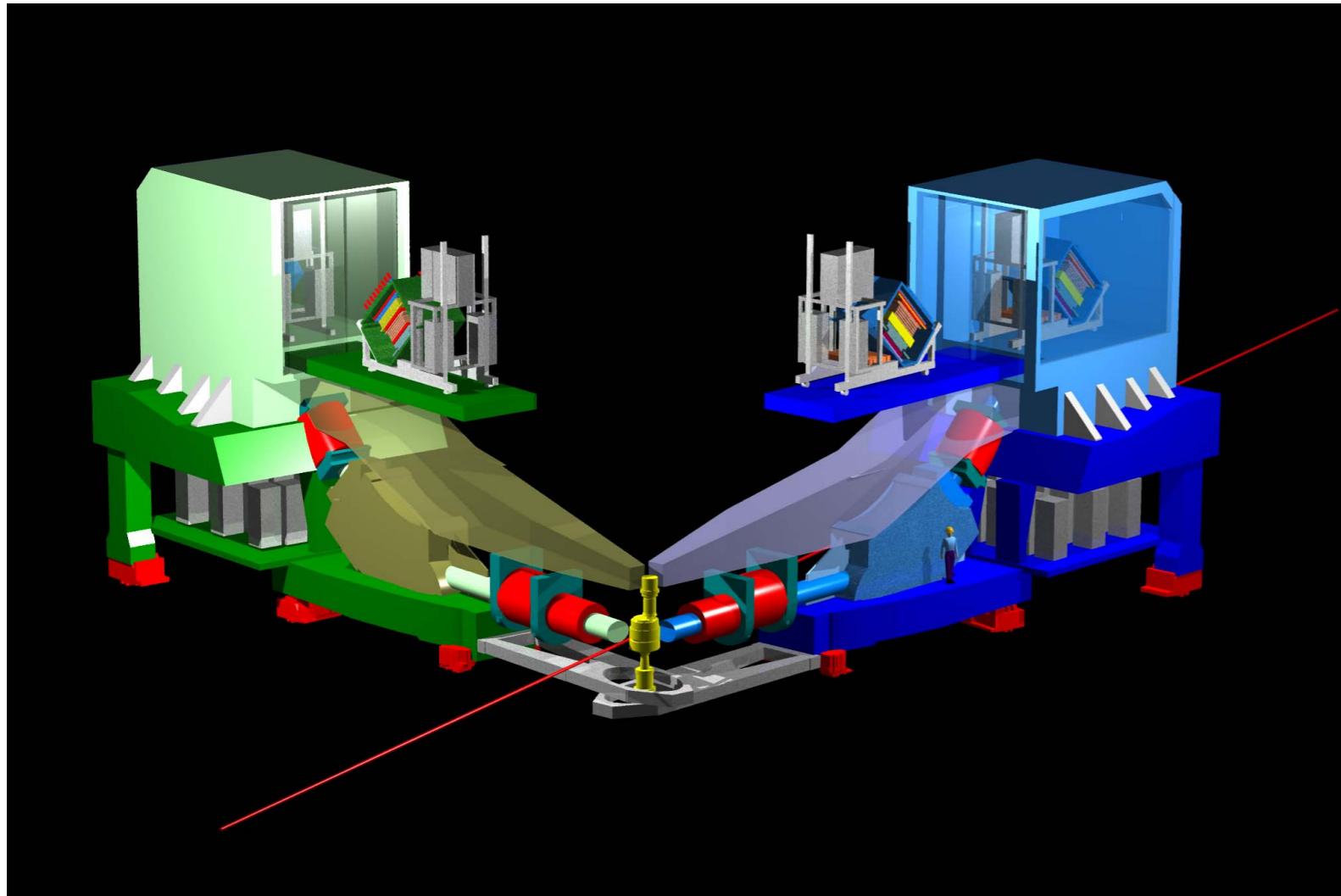
# JLab's Continuous Electron Beam Accelerator Facility



APEX in  
Hall A

two  
High-Resolution  
Spectrometers

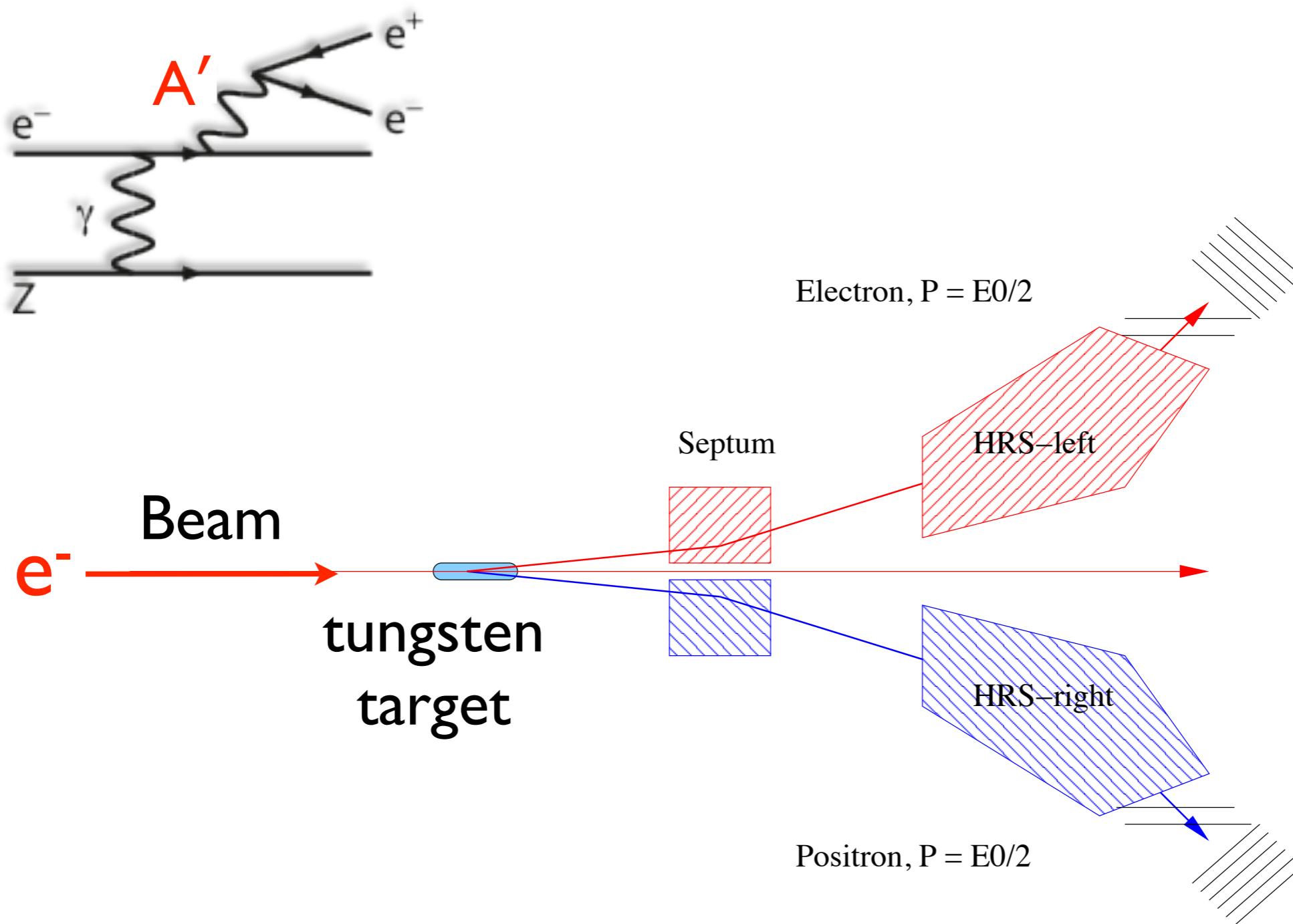
# High Resolution Spectrometers (HRS)



particle ID ( $e^-$ , pions, ...)

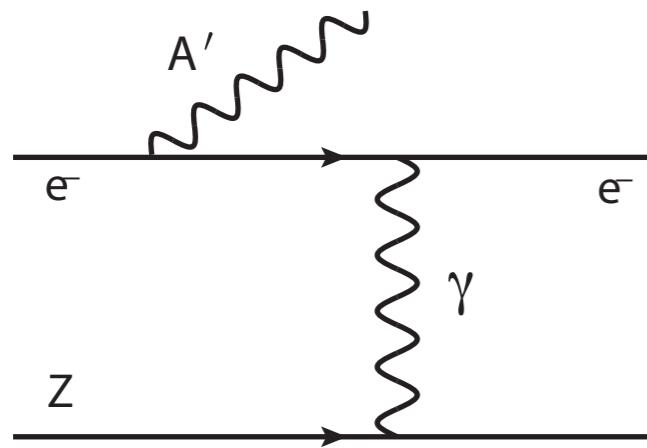
excellent  
momentum and  
angular resolution

# Experimental Setup

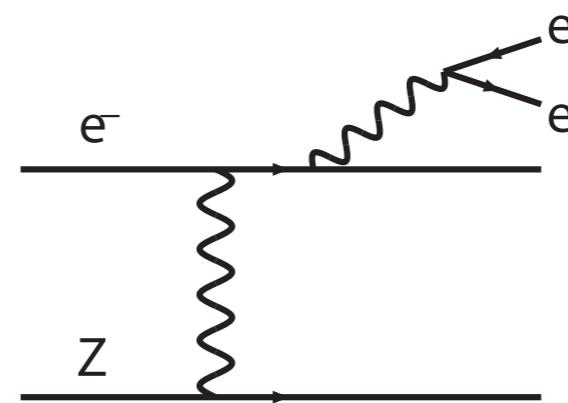


choose symmetric configuration (angles and energy)

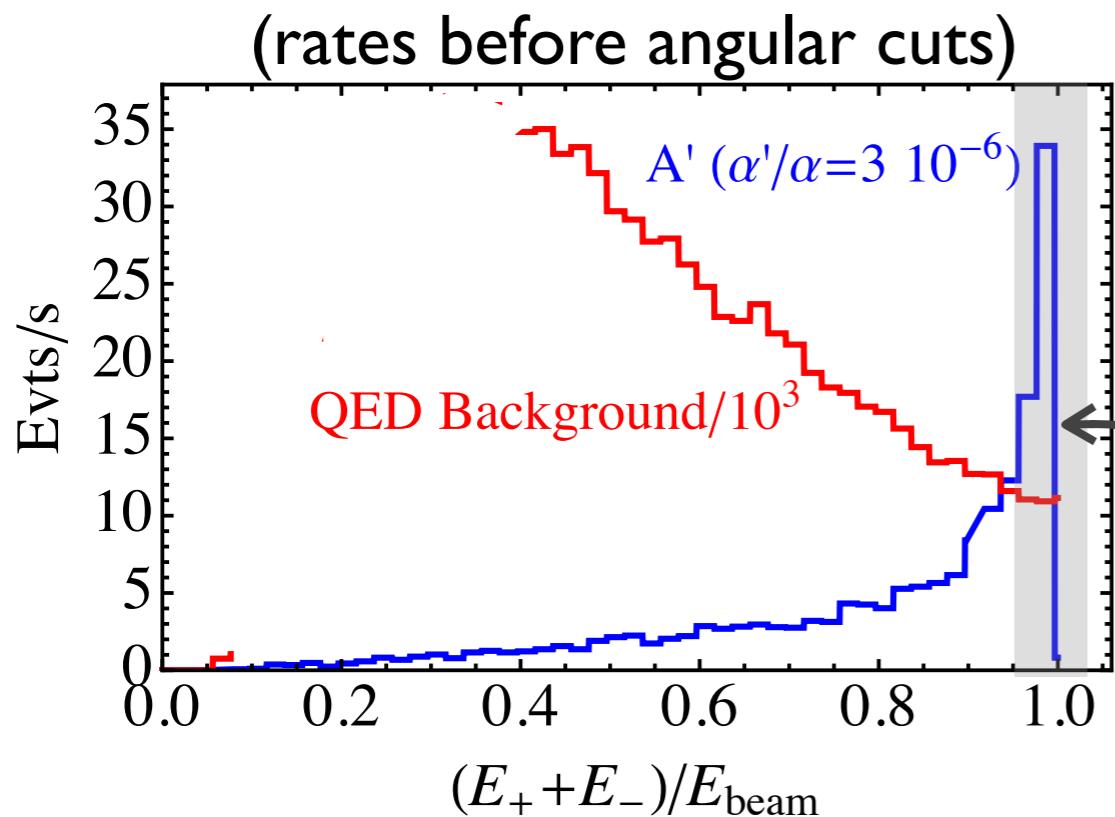
# Symmetric configuration maximizes signal over background



$A'$  signal



Backgrounds



$A'$  products carry (almost) full beam energy

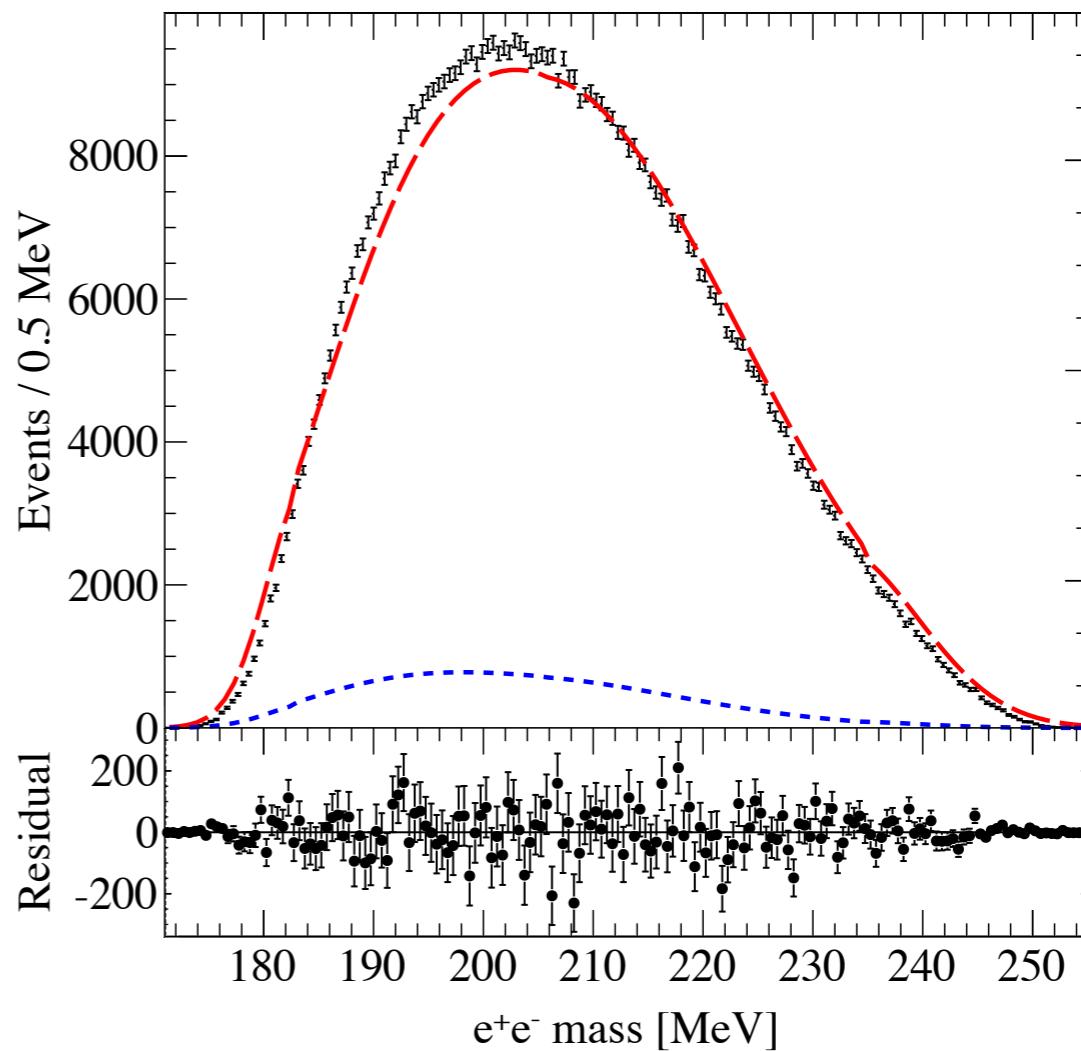
Symmetric energy, angles in two arms optimize  $A'$  acceptance

$$E^+ \approx E^- \approx E_{beam}/2$$

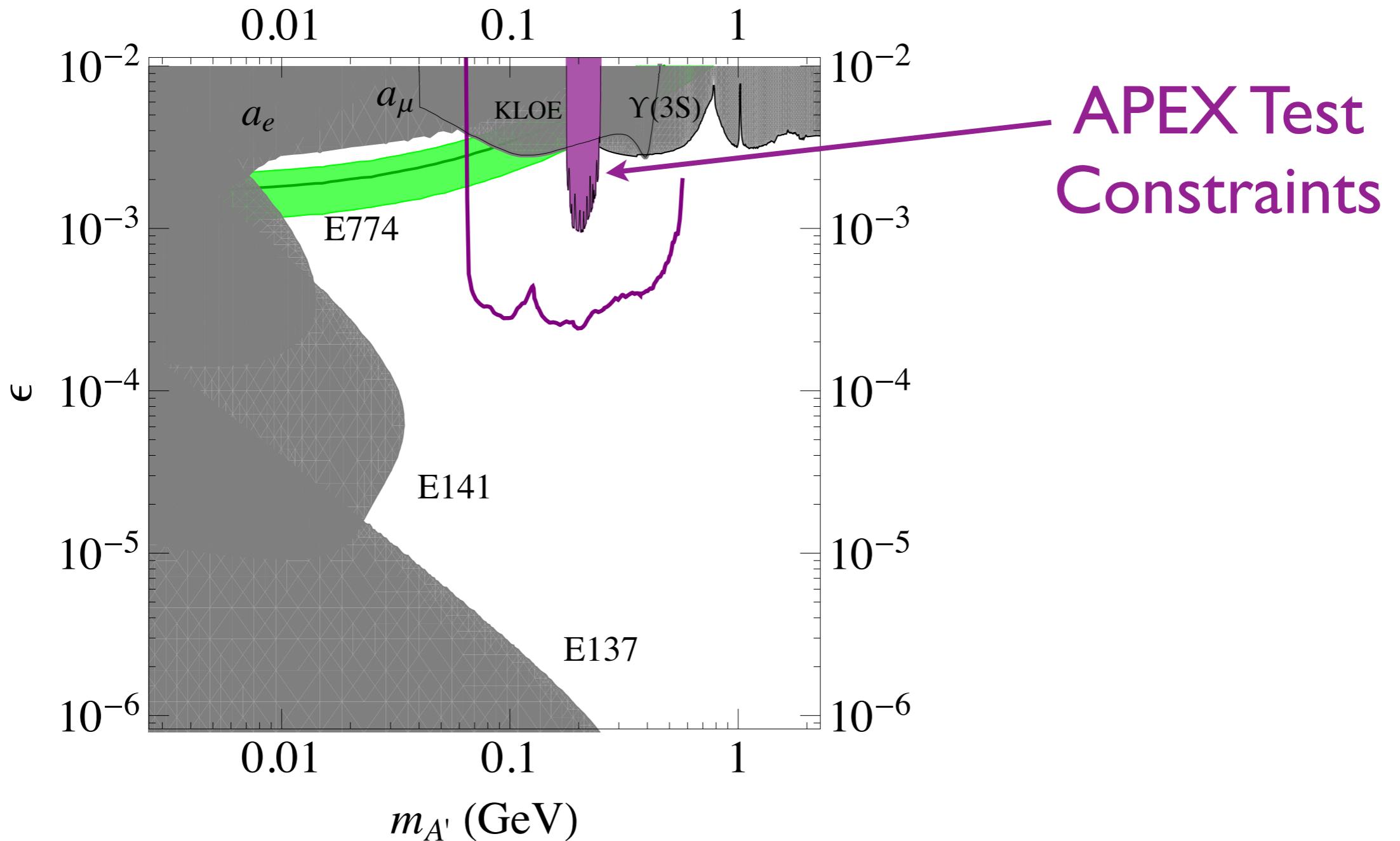
# APEX Test Run in July 2010

- Demonstrated many key elements for full experiment including
  - mass resolution
  - understanding of backgrounds
  - resonance search (on 700,000 good trident events)
- Results published in  
PRL 107 (2011) 191804

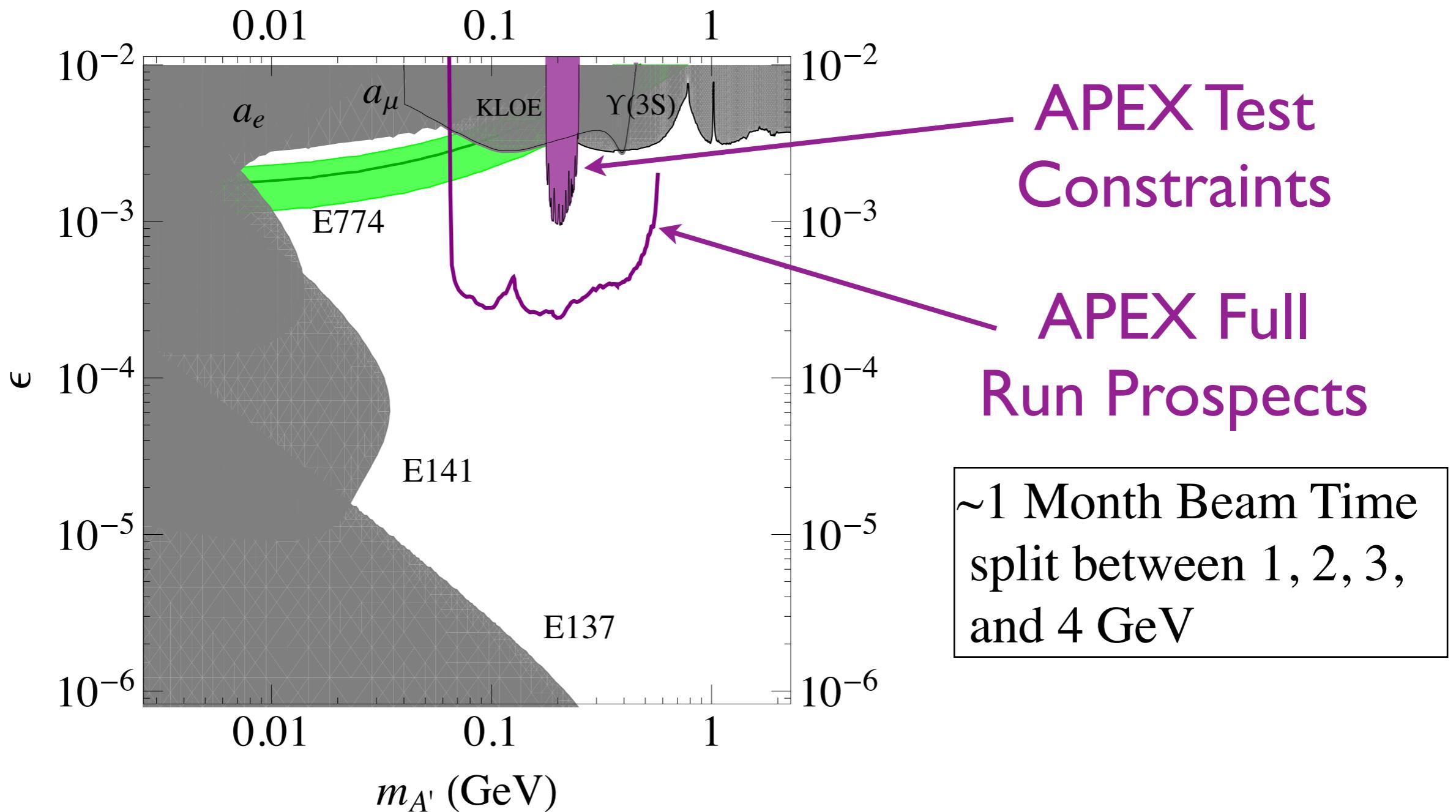
Invariant Mass Spectrum →



# Constraints and Prospects

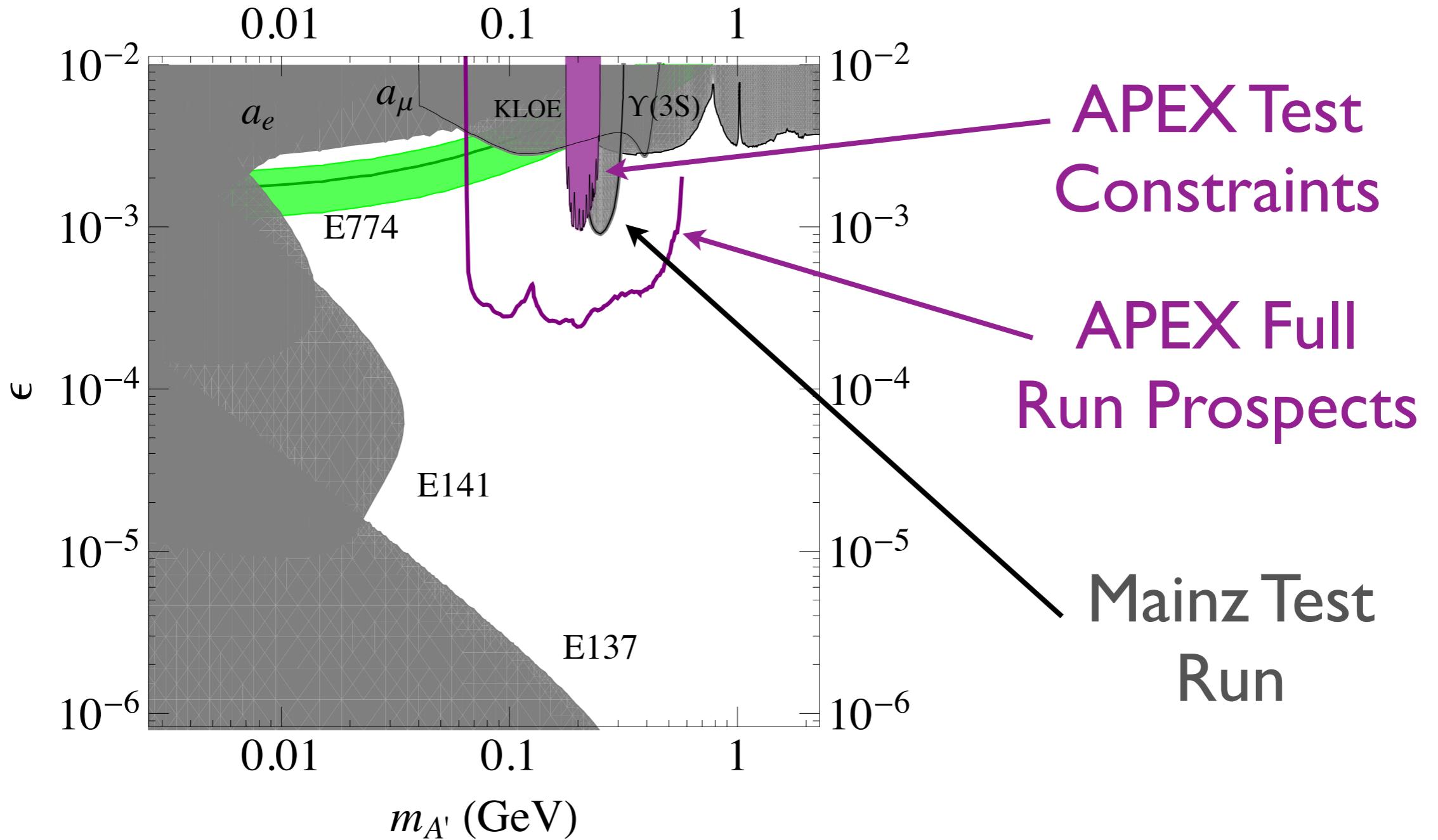


# Constraints and Prospects

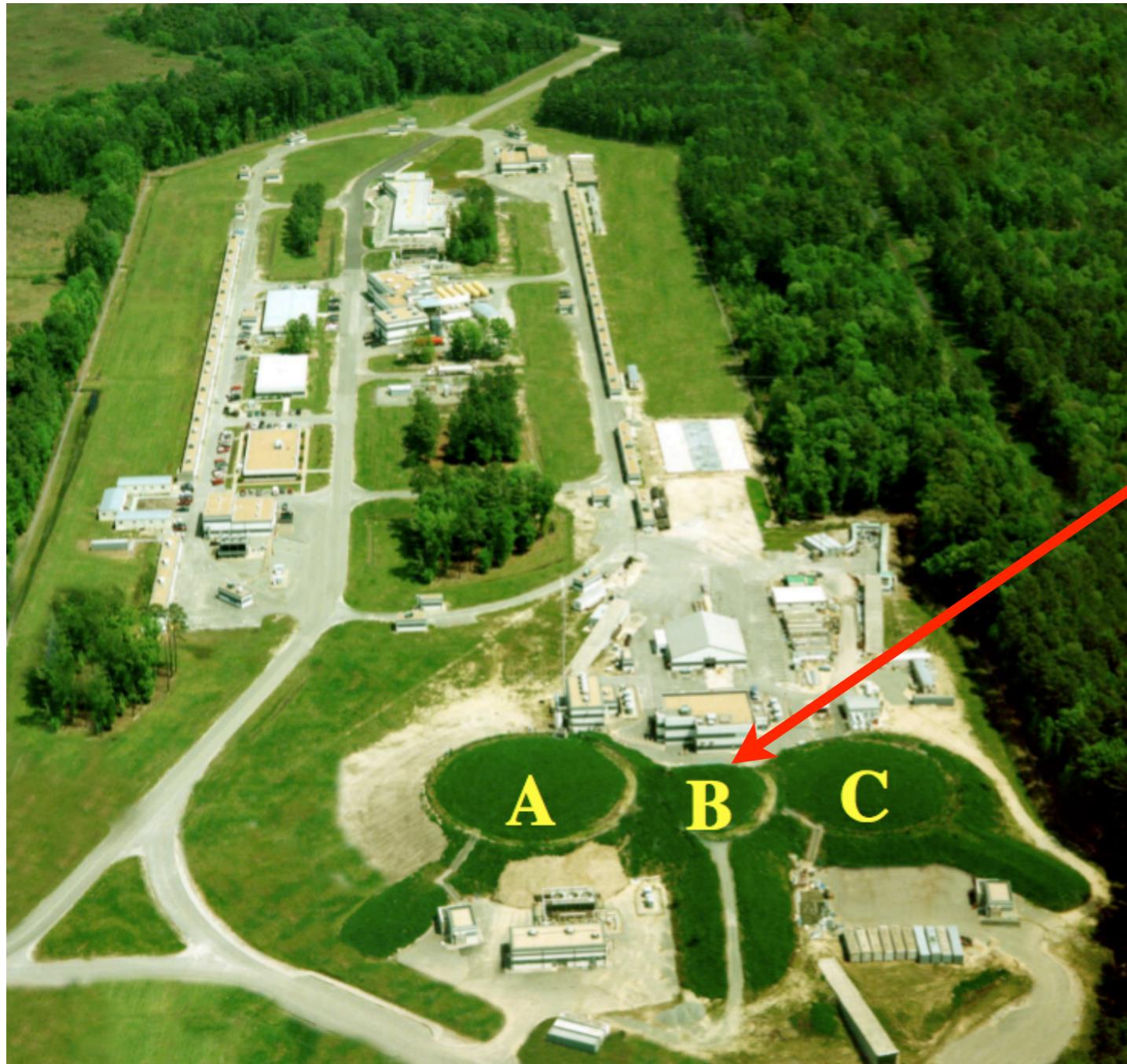


experiment approved  
planning underway for full run

# Constraints and Prospects



# Heavy Photon Search (HPS) @ JLab Hall B



HPS

# Heavy Photon Search (HPS) @ JLab Hall B

A. Grillo, V. Fadeyev

*University of California, Santa Cruz, CA 95064*

M. Ungaro

*University of Connecticut, Department of Physics, Storrs, CT 06269*

W. Cooper

*Fermi National Accelerator Laboratory, Batavia, IL 60510-5011*

A. Micherdzinska

*The George Washington University, Department of Physics, Washington, DC 20052*

G. Ron

*Hebrew University of Jerusalem, Jerusalem, Israel*

M. Battaglieri, R. De Vita

*INFN, Sezione di Genova, 16146 Genova, Italy*

M. Holtrop (Co-Spokesperson), K. Slifer, S. K. Phillips, E. Ebrahim

*University of New Hampshire, Department of Physics, Durham, NH 03824*

M. Khandaker, C. Salgado

*Norfolk State University, Department of Physics, Norfolk, VA 23504*

S. Bueltmann, L. Weinstein

*Old Dominion University, Department of Physics, Norfolk, VA 23529*

A. Fradi, B. Guegan, M. Guidal, S. Niccolai, S. Pisano, E. Rauly, P. Rosier and D. Sokhan

*Institut de Physique Nucléaire d'Orsay, 91405 Orsay, France*

P. Schuster, N. Toro

*Perimeter Institute, Ontario, Canada N2L 2Y5*

P. Stoler, A. Kubarovskiy

*Rensselaer Polytechnic Institute, Department of Physics, Troy, NY 12181*

R. Essig, C. Field, M. Graham, G. Haller, R. Herbst, J. Jaros (Co-Spokesperson), C. Kenney,

T. Maruyama, K. Moffeit, T. Nelson, H. Neal, A. Odian, M. Oriunno, R. Partridge, S. Uemura,

D. Walz

*SLAC National Accelerator Laboratory, Menlo Park, CA 94025*

S. Boyarinov, V. Burkert, A. Deur, H. Egiyan, L. Elouadrhiri, A. Freyberger, F.-X. Girod,  
V. Kubarovskiy, Y. Sharabian, S. Stepanyan (Co-Spokesperson), B. Wojtsekhowski

*Thomas Jefferson National Accelerator Facility, Newport News, VA 23606*

K. Griffioen

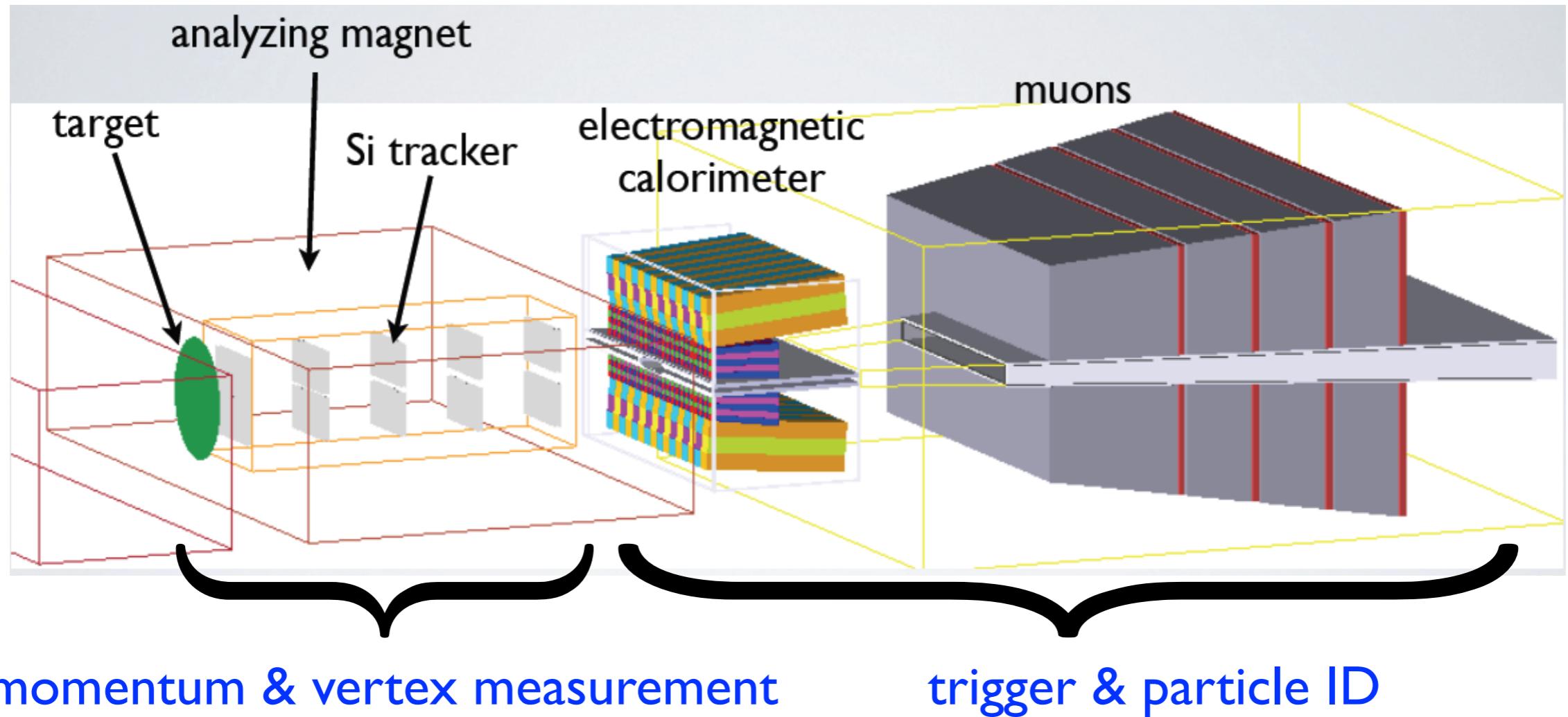
*The College of William and Mary, Department of Physics, Williamsburg, VA 23185*

N. Dashyan, N. Gevorgyan, R. Paremuzyan, H. Voskanyan

*Yerevan Physics Institute, 375036 Yerevan, Armenia*

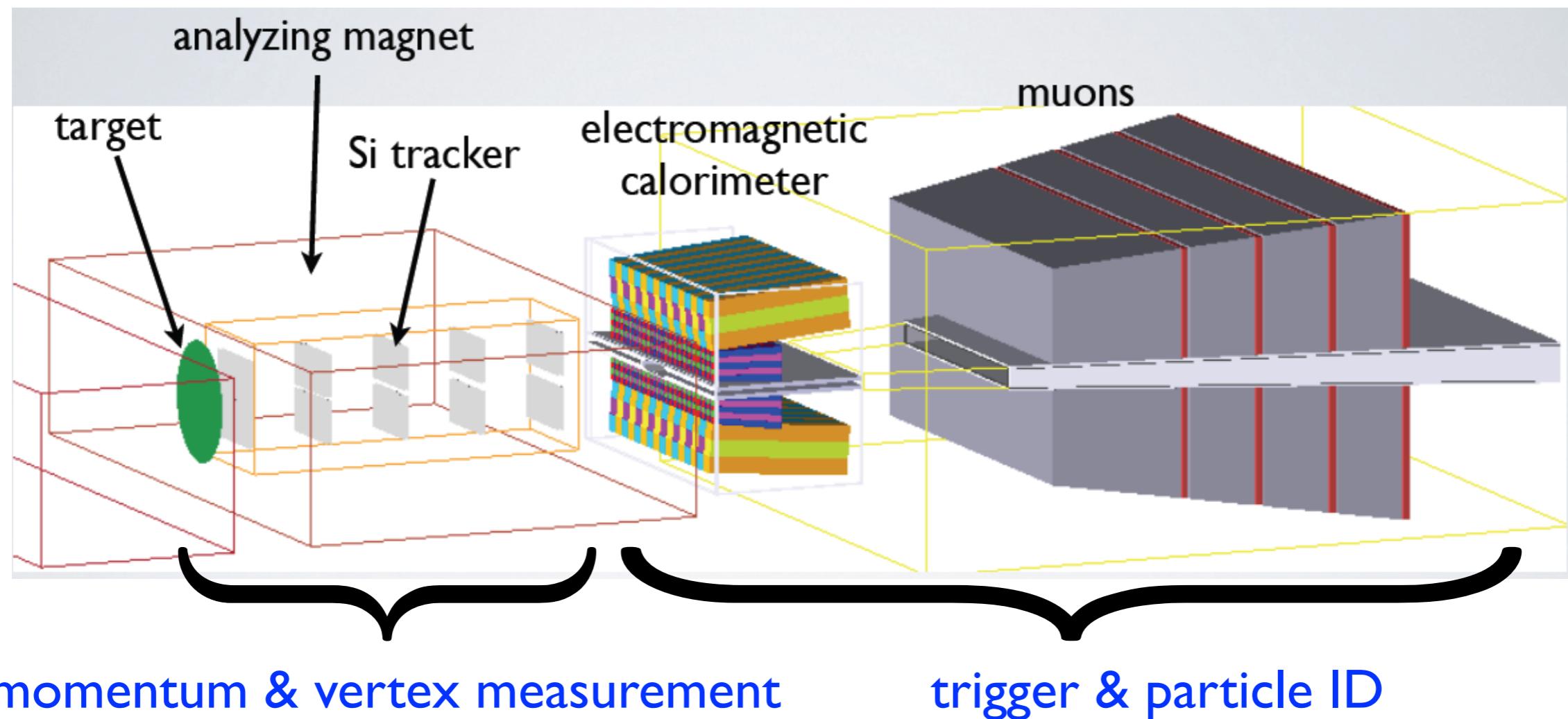
**Spokespeople:**  
**Maurik Holtrop**  
**John Jaros**  
**Stepan Stepanyan**

# HPS Experimental Setup and Status



with vertexing can probe smaller couplings

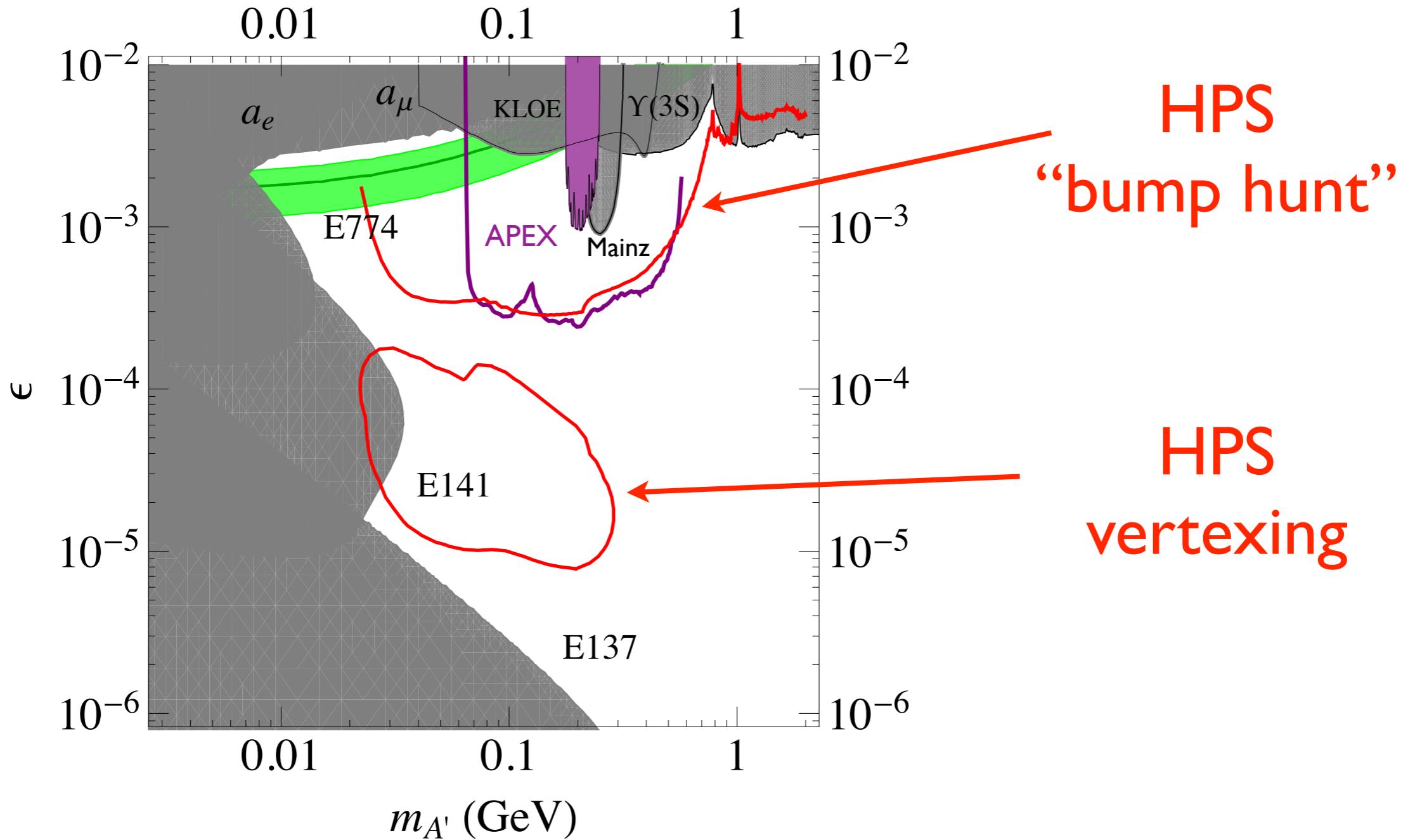
# HPS Experimental Setup and Status

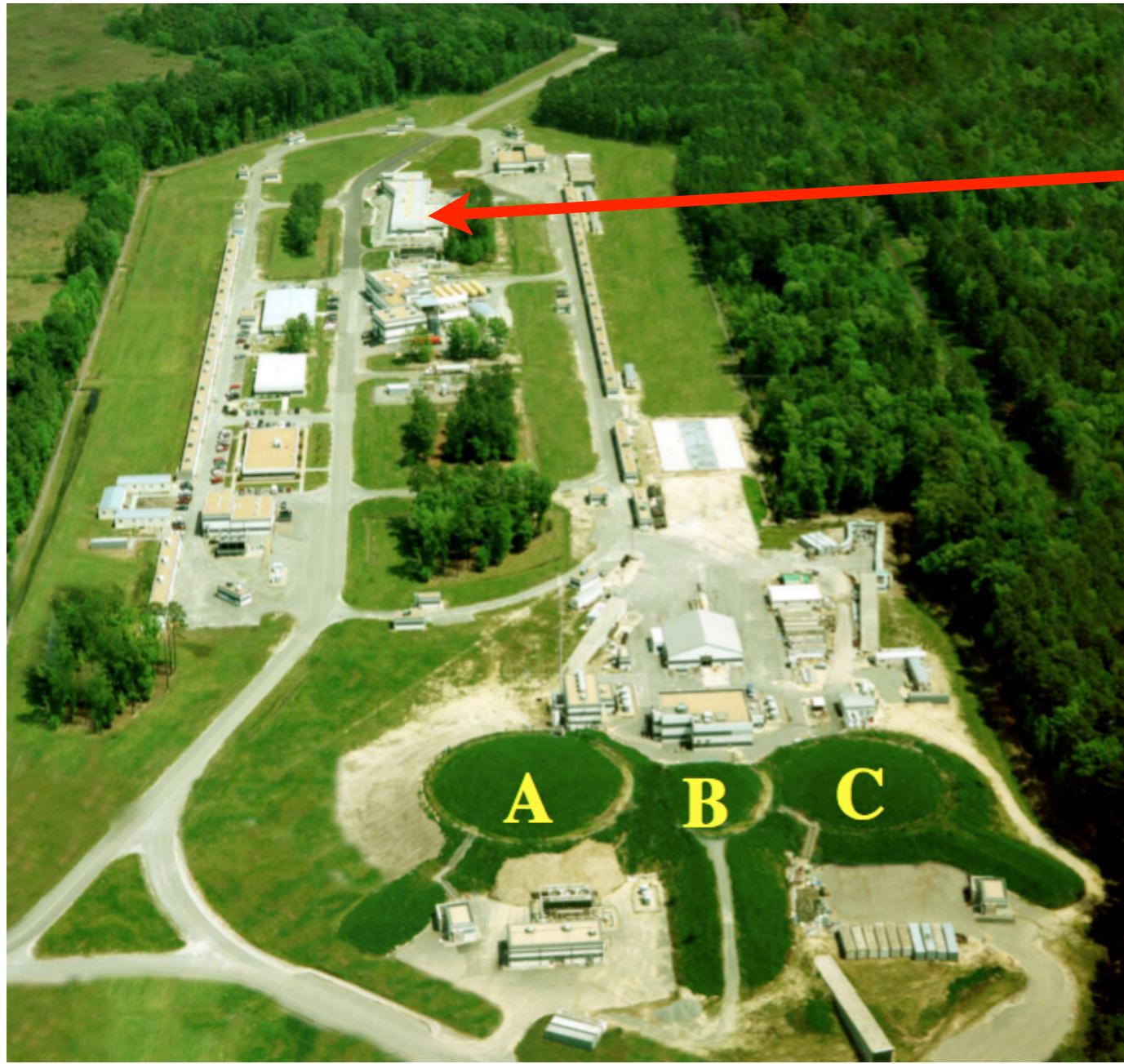


with **vertexing** can probe smaller couplings

- Proposal submitted Dec 2010
- Approval conditional on successful test run
- Requested test run in 6 GeV era & 6-month run after JLab upgrade

# Constraints and Prospects





uses the  $e^-$  beam  
of JLab's Free  
Electron Laser (FEL)



P. Balakrishnan, J. Balewski, J. Bernauer, W.  
Bertozzi, R. Cowan, K. Dow, C. Epstein, P. Fisher,  
S. Gilad, E. Ihloff, Y. Kahn, A. Kelleher, J. Kelsey, R.  
Milner, R. Russell, J. Thaler, C. Tschalaer, A.  
Winnebeck  
*Laboratory for Nuclear Science, M.I.T.*

R. Fiorito, P. O'Shea  
*Institute for Research in Electronics and Applied  
Physics, University of Maryland*  
R. Alarcon, R. Dipert  
*Physics Department, Arizona State University*

S. Benson, J. Boyce, D. Douglas, R. Ent, P.  
Evtushenko, H. C. Fenker, J. Gubeli, F. Hannon, J.  
Huang, K. Jordan, G. Neil, T. Powers, D. Sexton,  
M. Shinn, C. Tennant, S. Zhang  
*Jefferson Lab*

B. Surrow  
*Temple University*  
G. Ovanesyan  
*Los Alamos National Laboratory*

M. Freytsis  
*Physics Dept. U.C. Berkeley*

M. Kohl  
*Physics Dept., Hampton University*  
T. Horn  
*Physics Dept., Catholic University of America*



## Detecting A Resonance Kinematically with eLectrons Incident on a Gaseous Hydrogen Target

uses 100 MeV, 10 mA e<sup>-</sup> beam on hydrogen gas target

sensitive to invisible A' decays

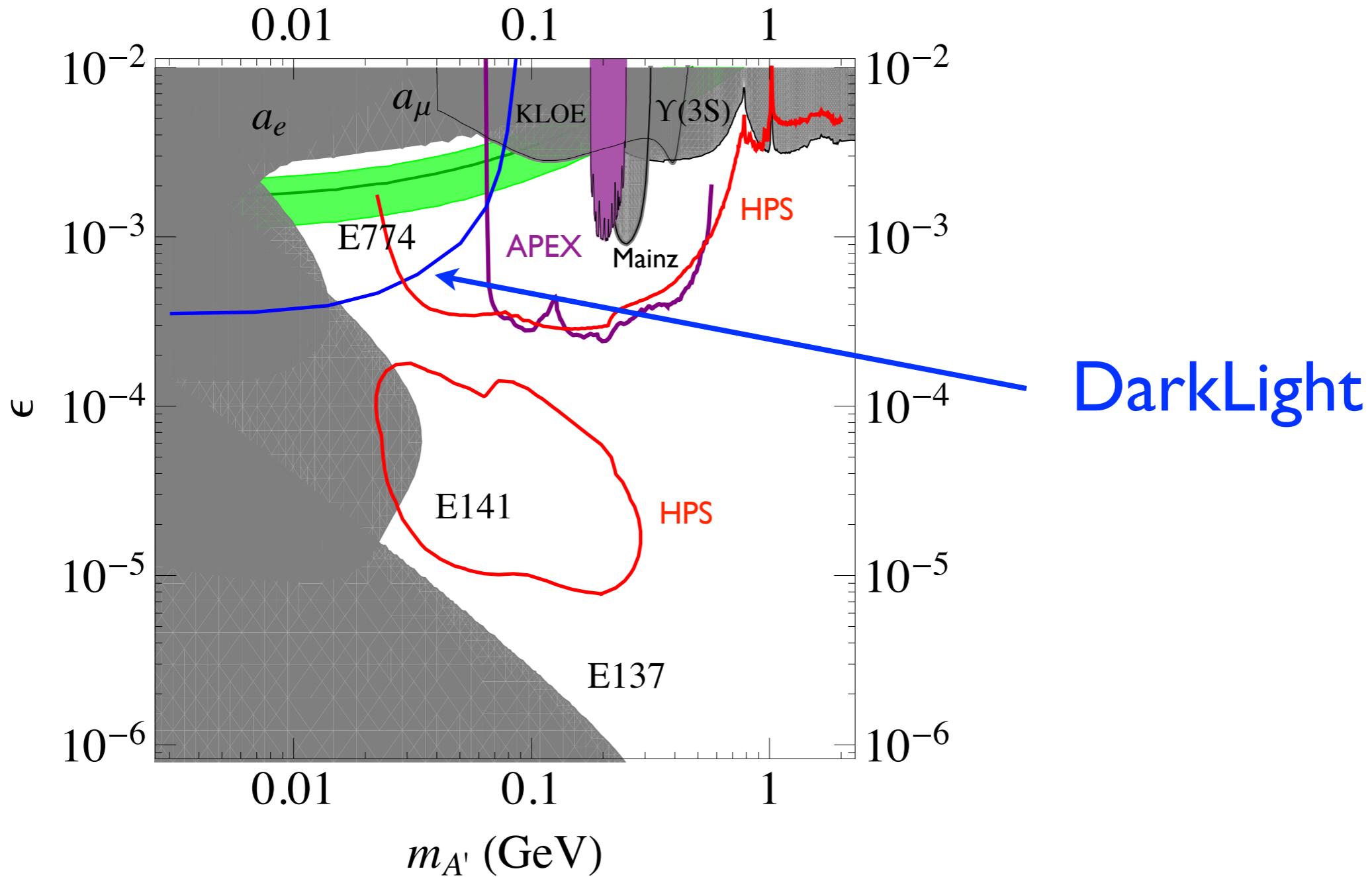
### Status:

Submit full proposal to JLab in June 2012

Start construction in late 2012

Data in 2015

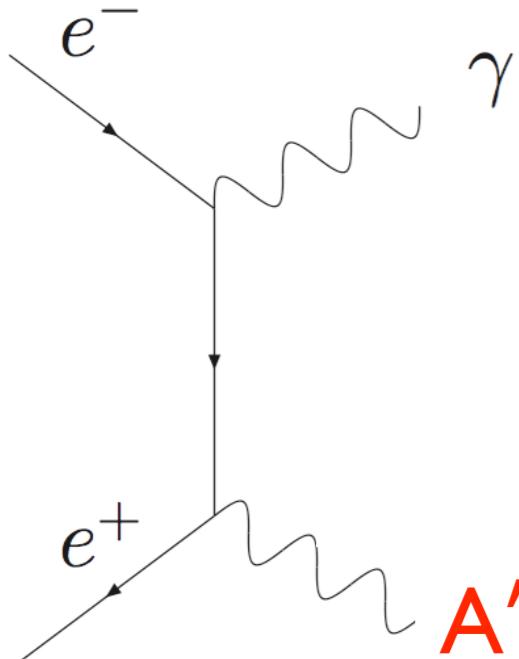
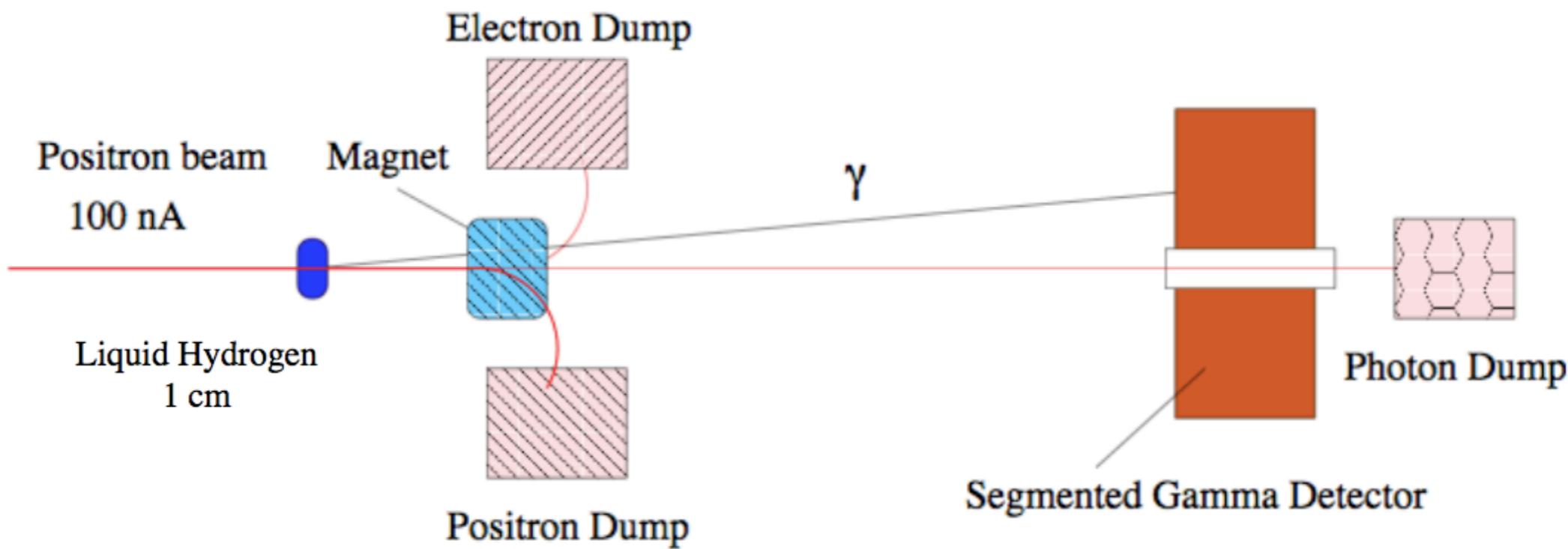
# Constraints and Prospects



# VEPP-3

Wojtsekhowski et.al.

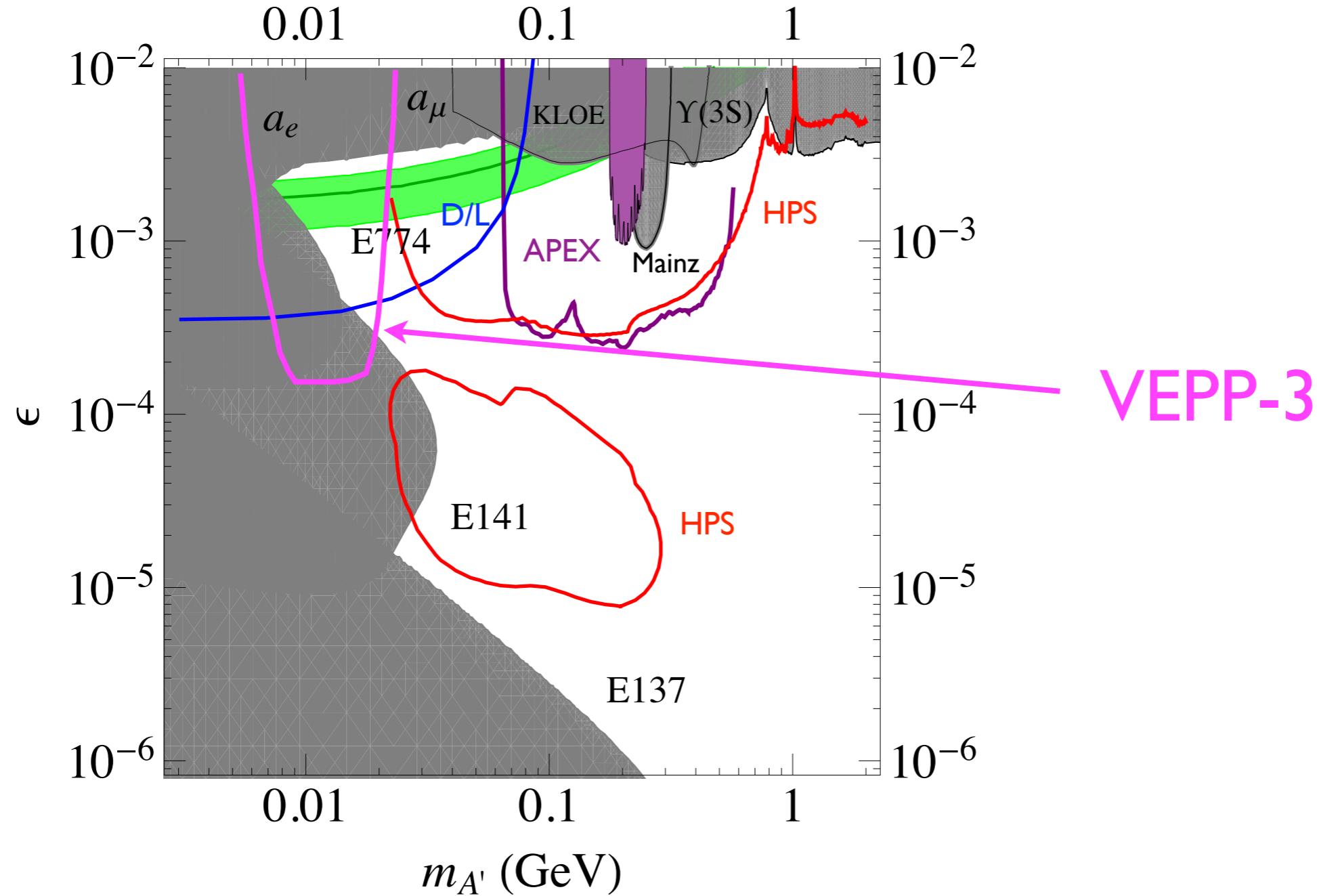
@ Budker Institute of Nuclear Physics, Novosibirsk, Russia



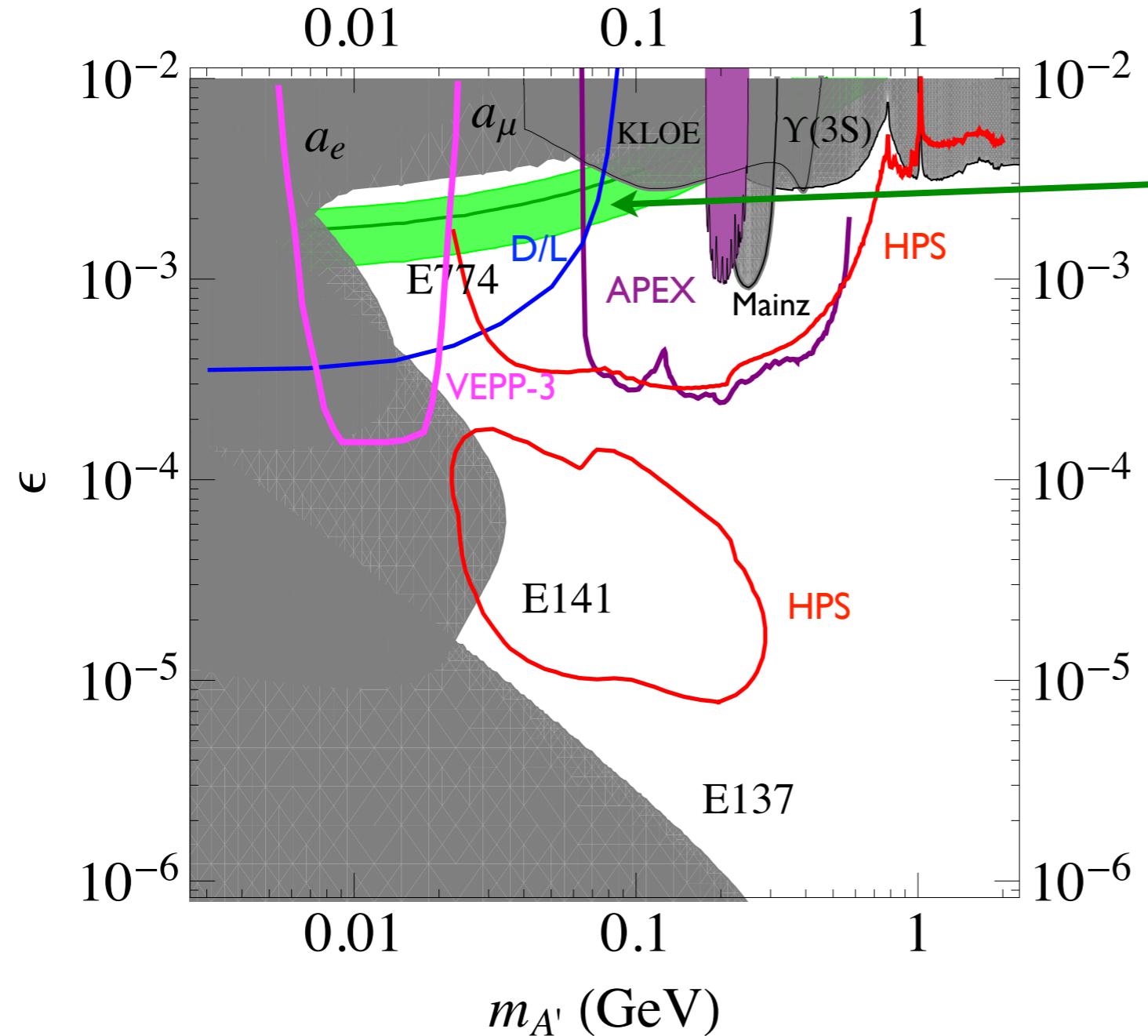
~500 MeV positron beam  
on liquid hydrogen target

look for  $A'$  resonance or detect only  
photon (sensitive to invisible  $A'$  decays)

# Constraints and Prospects



# Summary



muon  $g_s - 2$ :  
whole region will  
be covered

assumes  $A'$   
decays directly to  
Standard Model

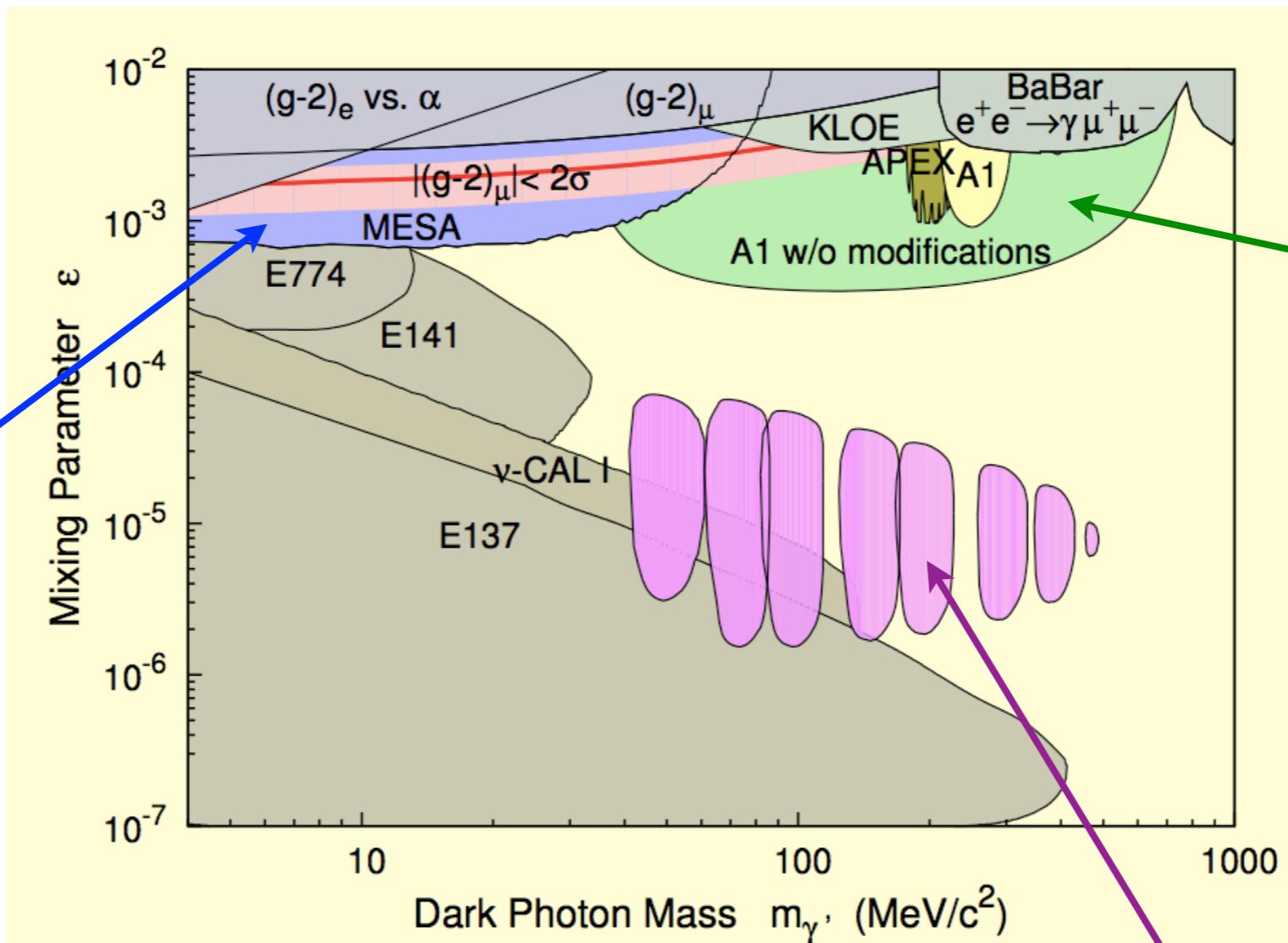
but DarkLight &  
VEPP-3 sensitive  
to invisible  $A'$   
decays

region motivated by theory, dark matter, muon  $g_s - 2$

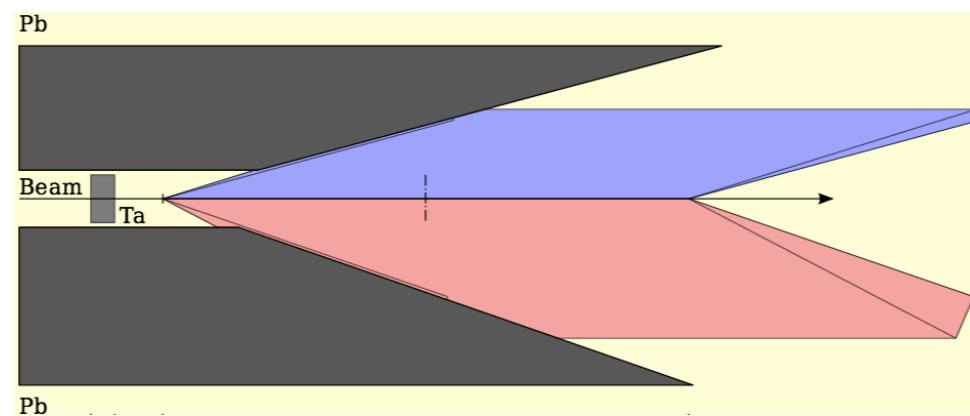
# Plans at Mainz

see talk by H. Merkel at  
Intensity Frontier Workshop,  
Rockville MD, 2011

DarkLight-like  
setup using  
MAMI's FEL

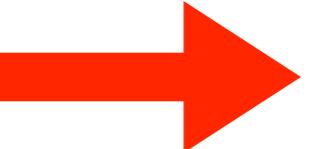
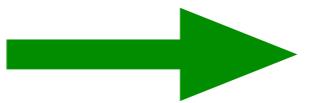


APEX-like  
setup



Vertexing:  
shield target  
region

# Outline

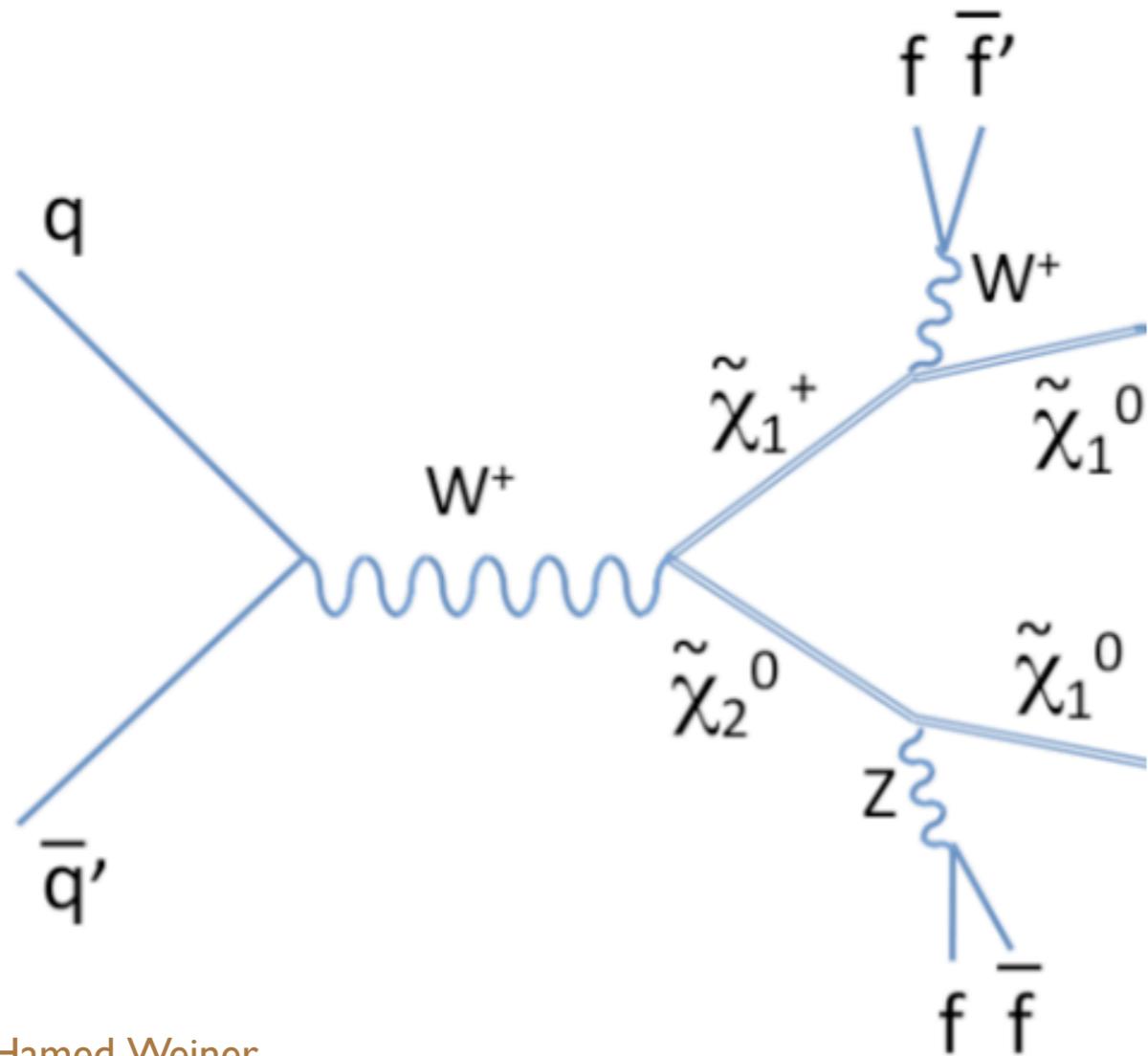
- Theory
  - Motivation (“hints”)
  - Searches
    - $e^+e^-$  colliders
    - fixed target:  $e^-$  and  $p$
    - Tevatron & LHC
- 
- 

mention one example only very briefly...

# Collider Signals, assuming SUSY exists

cf. "Hidden Valley" models  
Strassler et.al. [2006]

## Produce $A'$ through supersymmetry



a typical collider  
event in  
supersymmetry...

Arkani-Hamed, Weiner

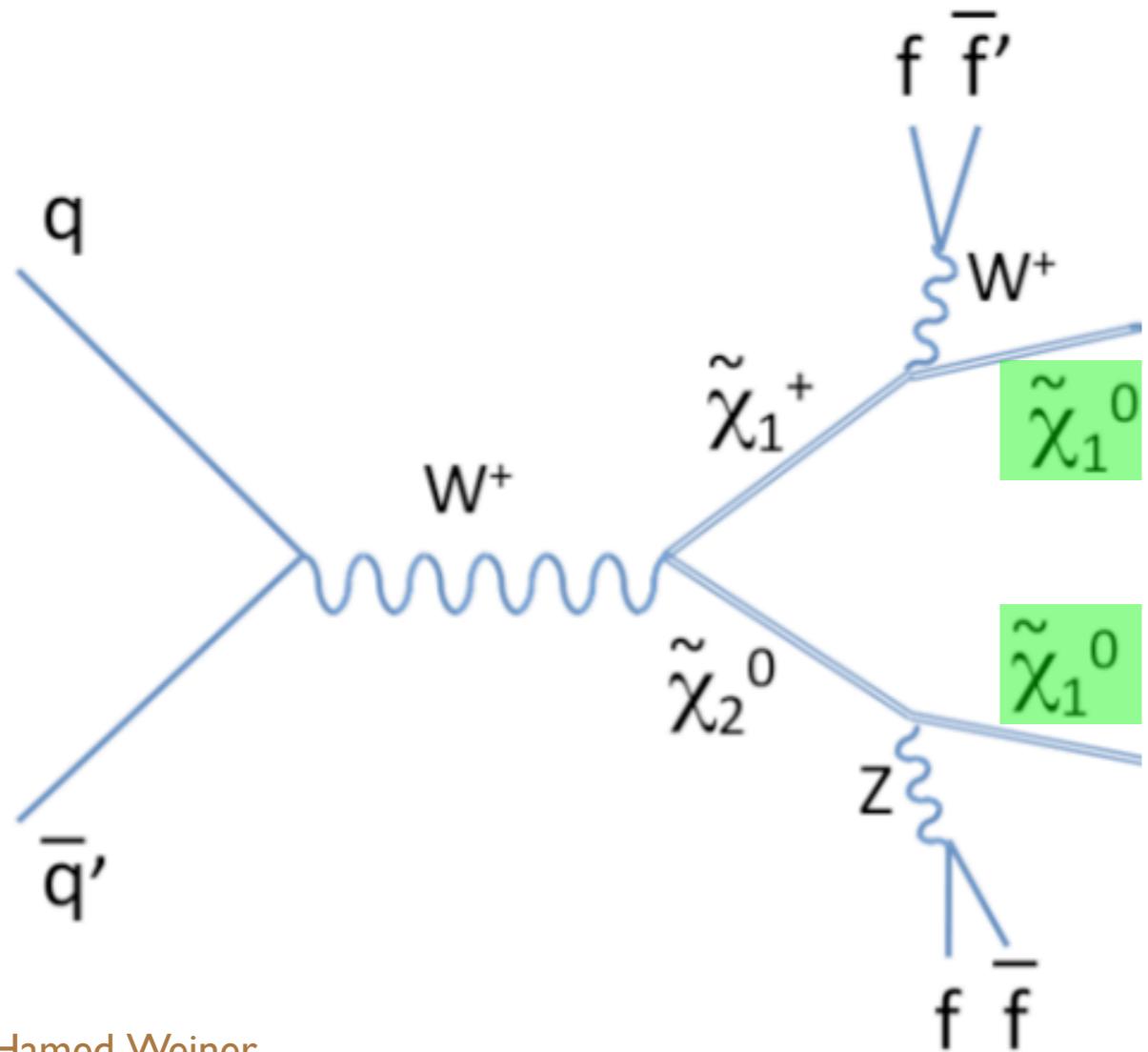
Baumgart, Cheung, Ruderman, Wang, Yavin

Shih, Thomas

# Collider Signals, assuming SUSY exists

cf. “Hidden Valley” models  
Strassler et.al. [2006]

## Produce $A'$ through supersymmetry



a typical collider  
event in  
supersymmetry...

Lightest SUSY  
particle (“LSP”)  
is often stable...

Arkani-Hamed, Weiner

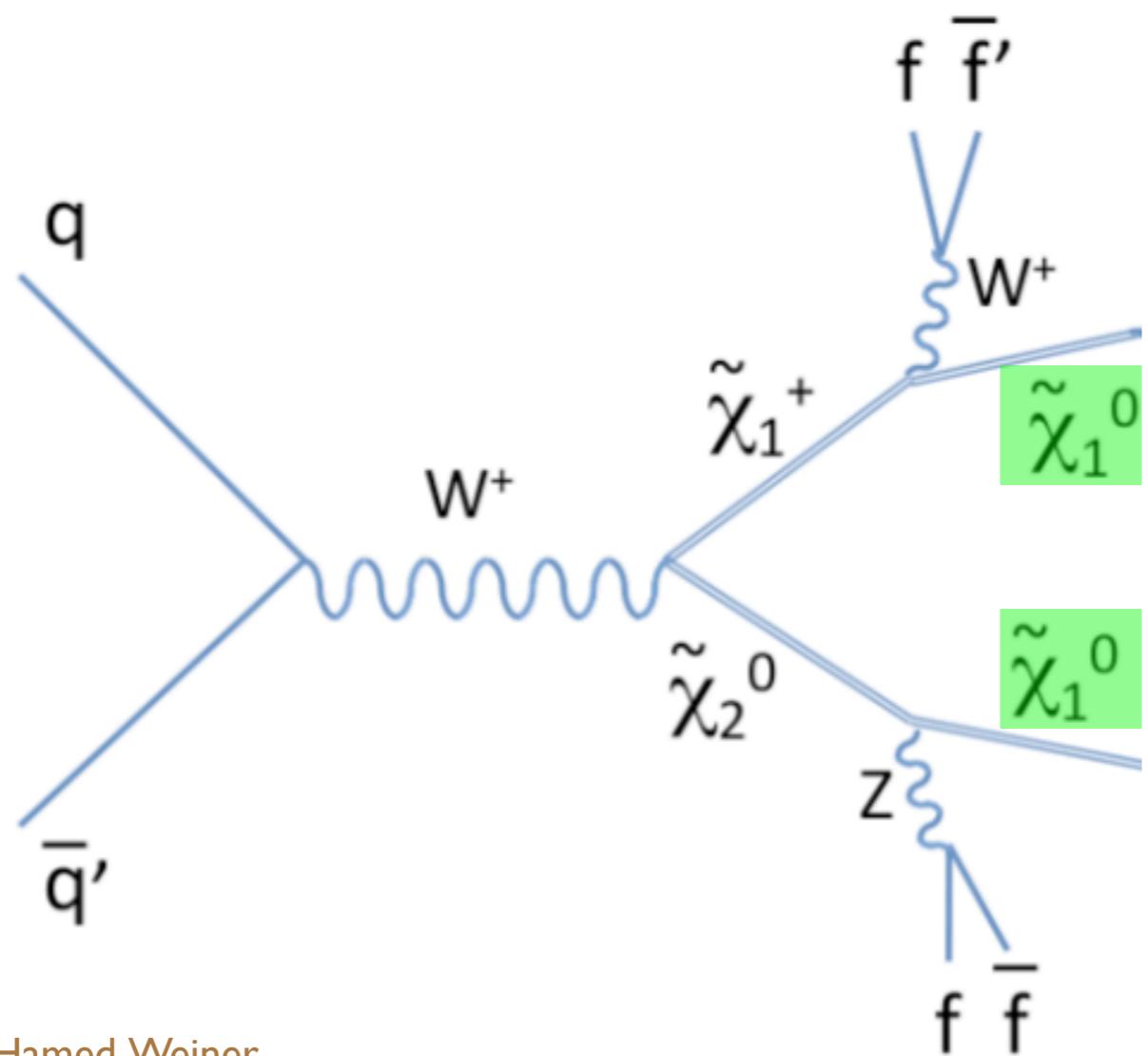
Baumgart, Cheung, Ruderman, Wang, Yavin

Shih, Thomas

# Collider Signals, assuming SUSY exists

cf. “Hidden Valley” models  
Strassler et.al. [2006]

## Produce $A'$ through supersymmetry



But with an  $A'$ :  
Lightest SUSY  
particle (“LSP”)  
is *unstable*...

Arkani-Hamed, Weiner

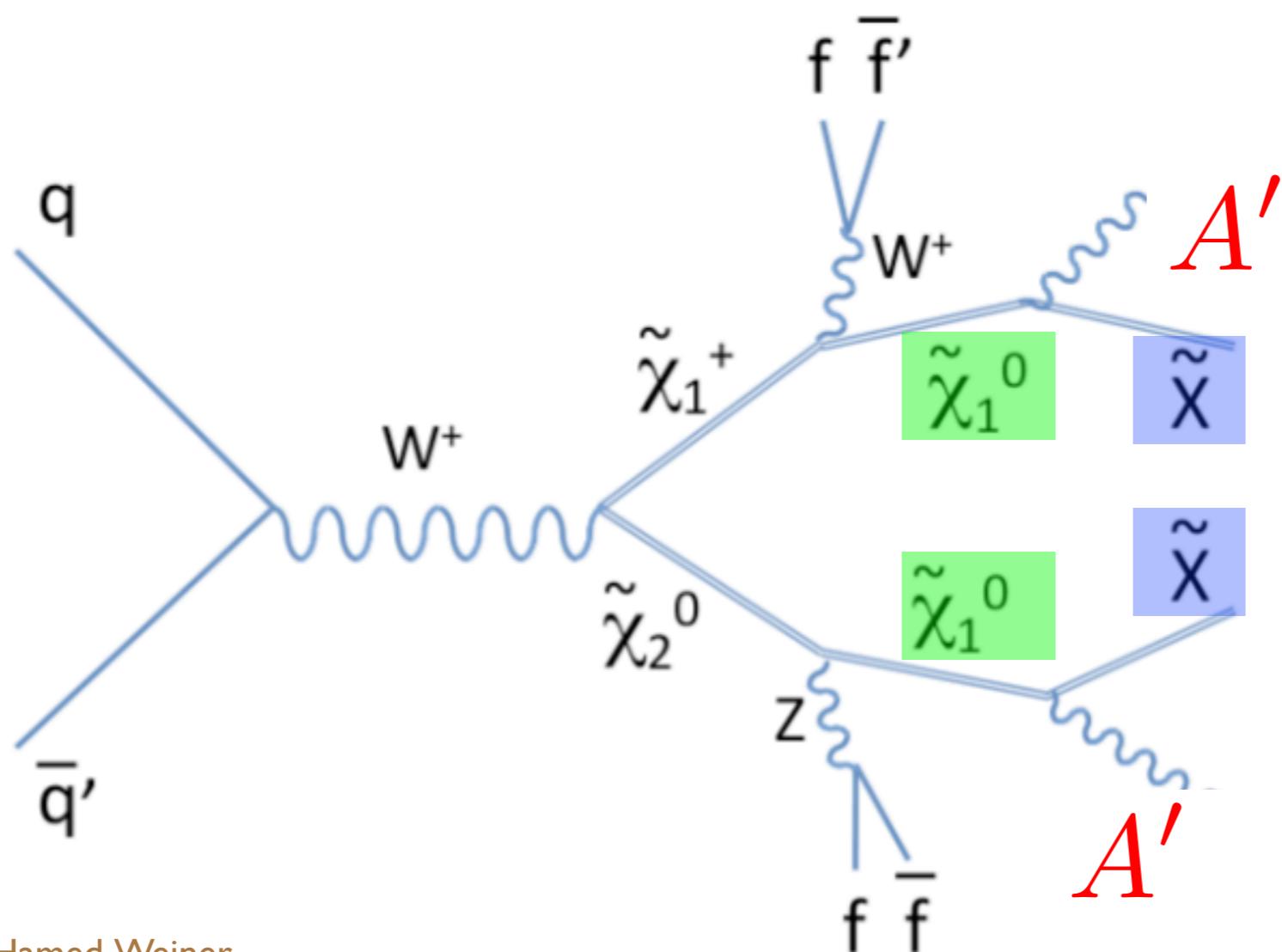
Baumgart, Cheung, Ruderman, Wang, Yavin

Shih, Thomas

# Collider Signals, assuming SUSY exists

cf. “Hidden Valley” models  
Strassler et.al. [2006]

## Produce $A'$ through supersymmetry



But with an  $A'$ :  
Lightest SUSY  
particle (“LSP”)  
is *unstable*...  
decays to  
 $A'$  + hidden  
sector

Arkani-Hamed, Weiner

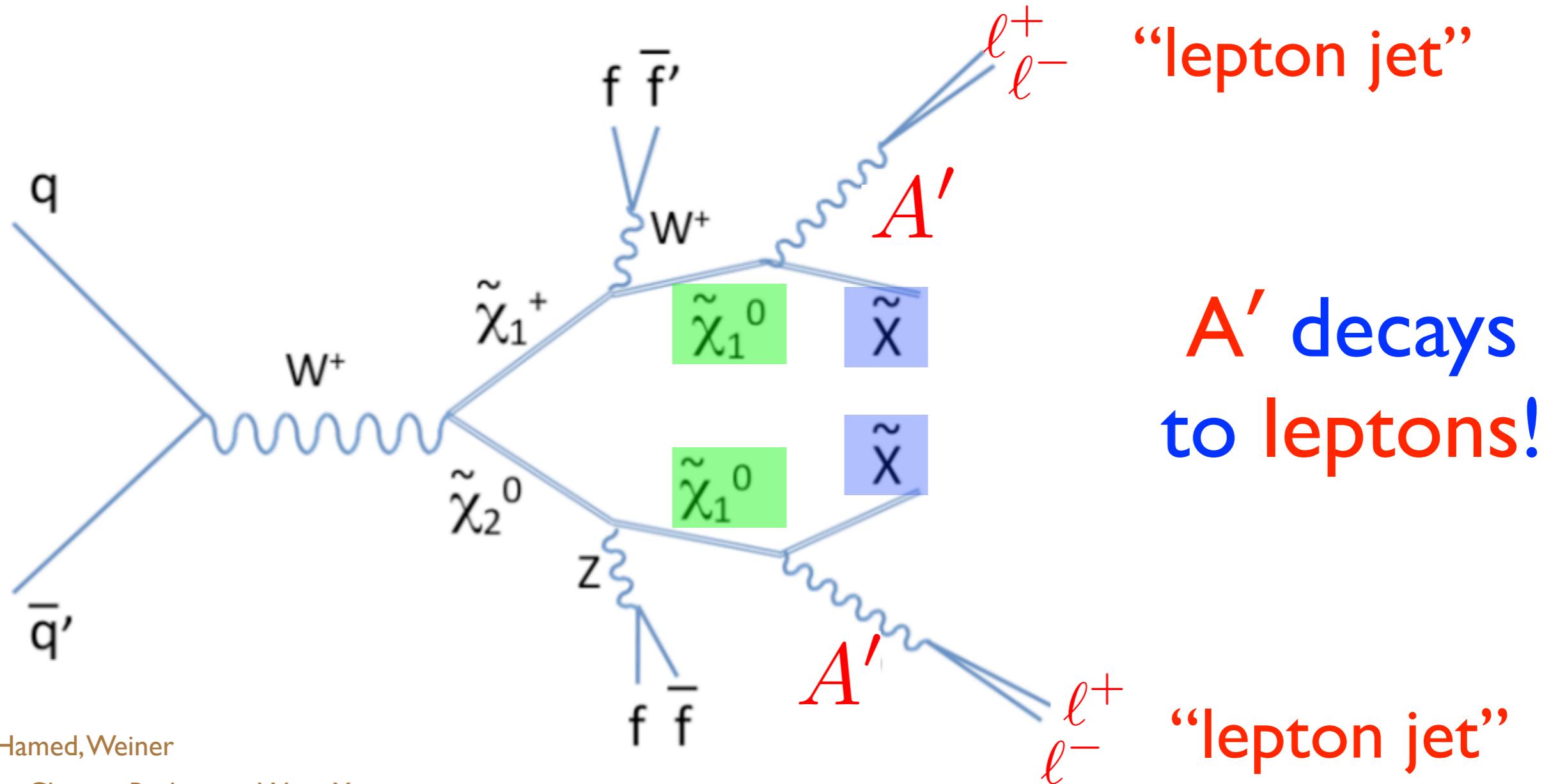
Baumgart, Cheung, Ruderman, Wang, Yavin

Shih, Thomas

# Collider Signals, assuming SUSY exists

cf. “Hidden Valley” models  
Strassler et.al. [2006]

## Produce $A'$ through supersymmetry

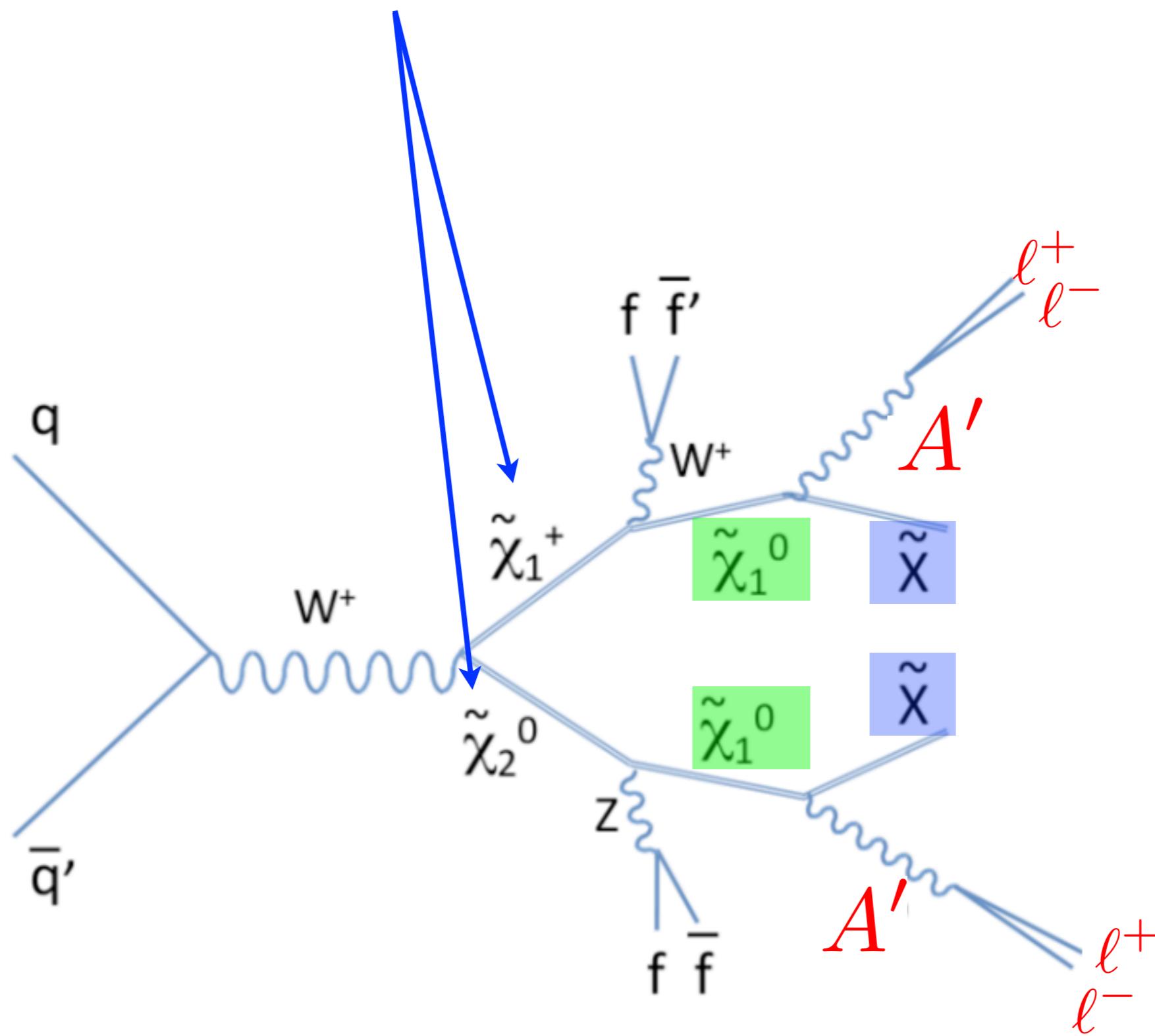


Arkani-Hamed, Weiner

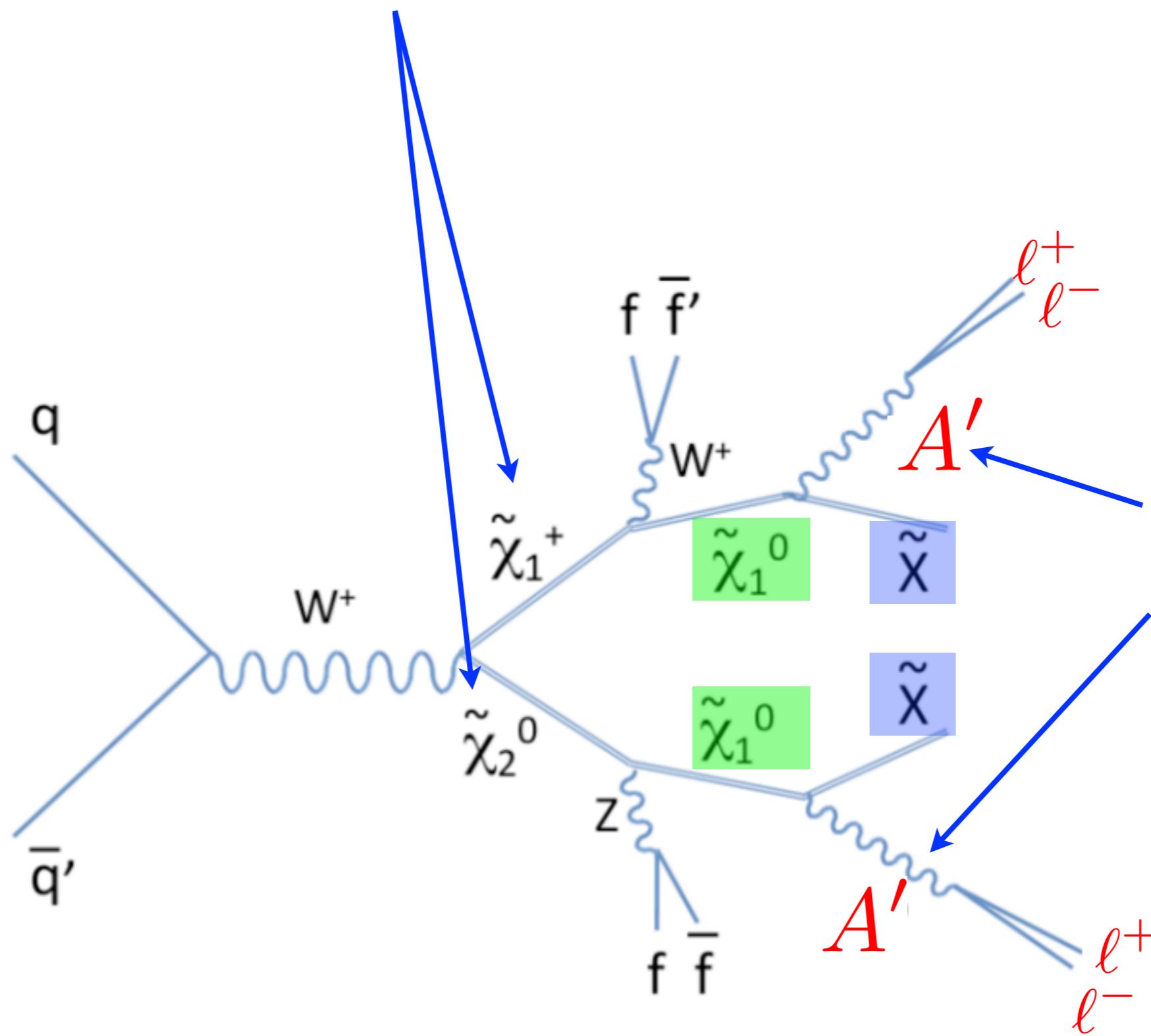
Baumgart, Cheung, Ruderman, Wang, Yavin

Shih, Thomas

If SUSY particles too heavy, then can't produce these events

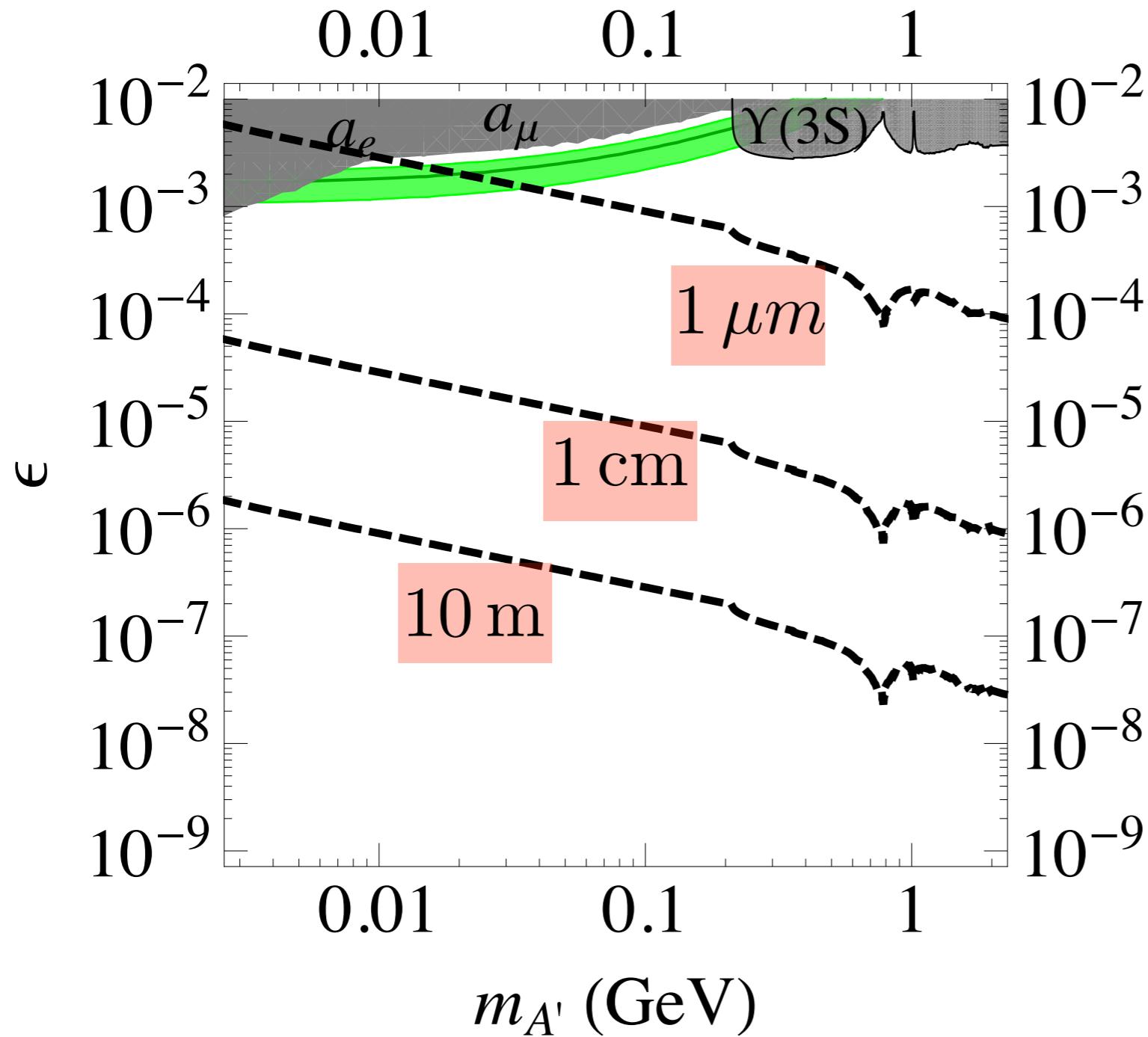


If SUSY particles too heavy, then can't produce these events

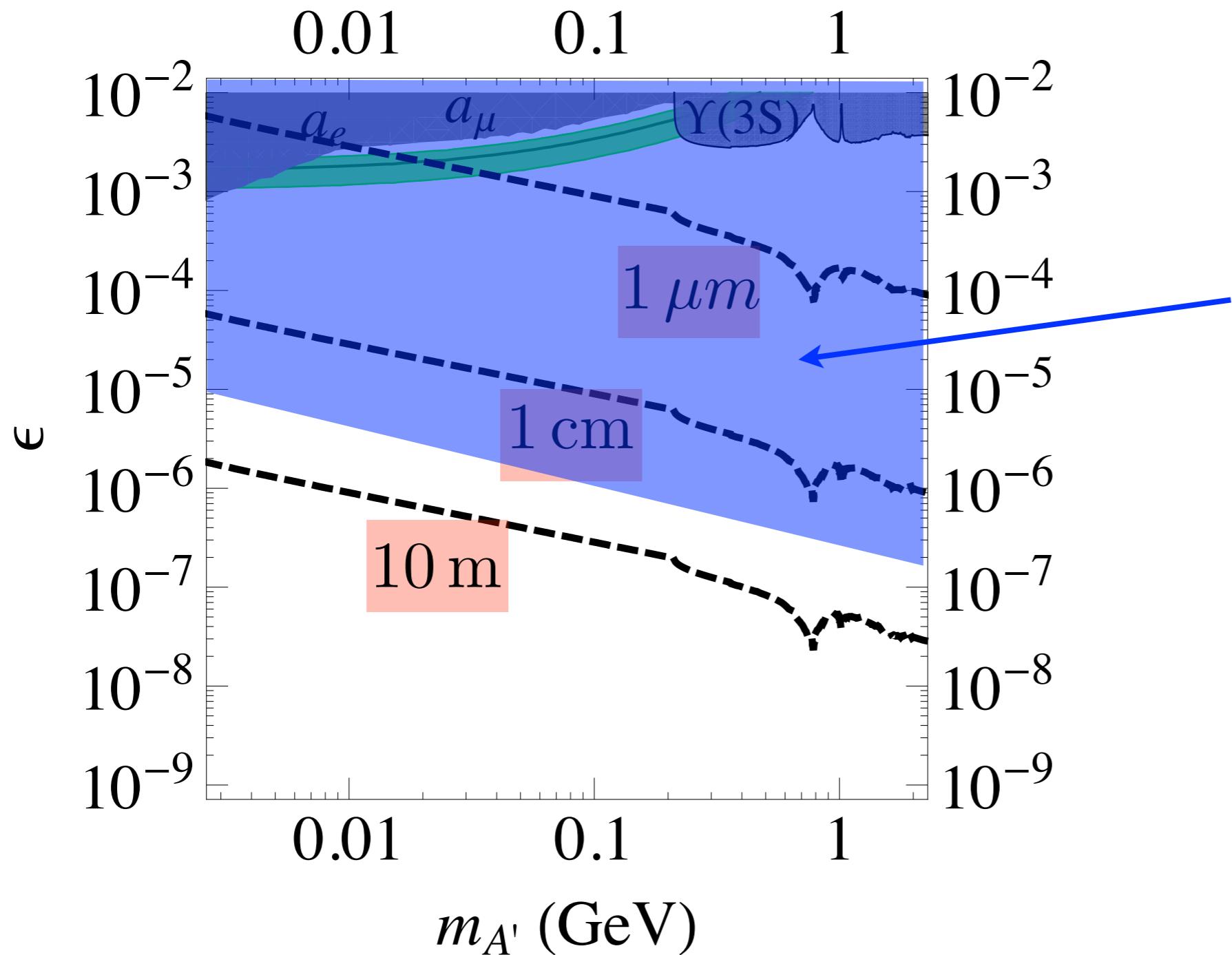


and need to  
assume  $A'$  decays  
inside detector  
(i.e. lifetime is  
not too long)

# $A'$ lifetime varies by orders of magnitude



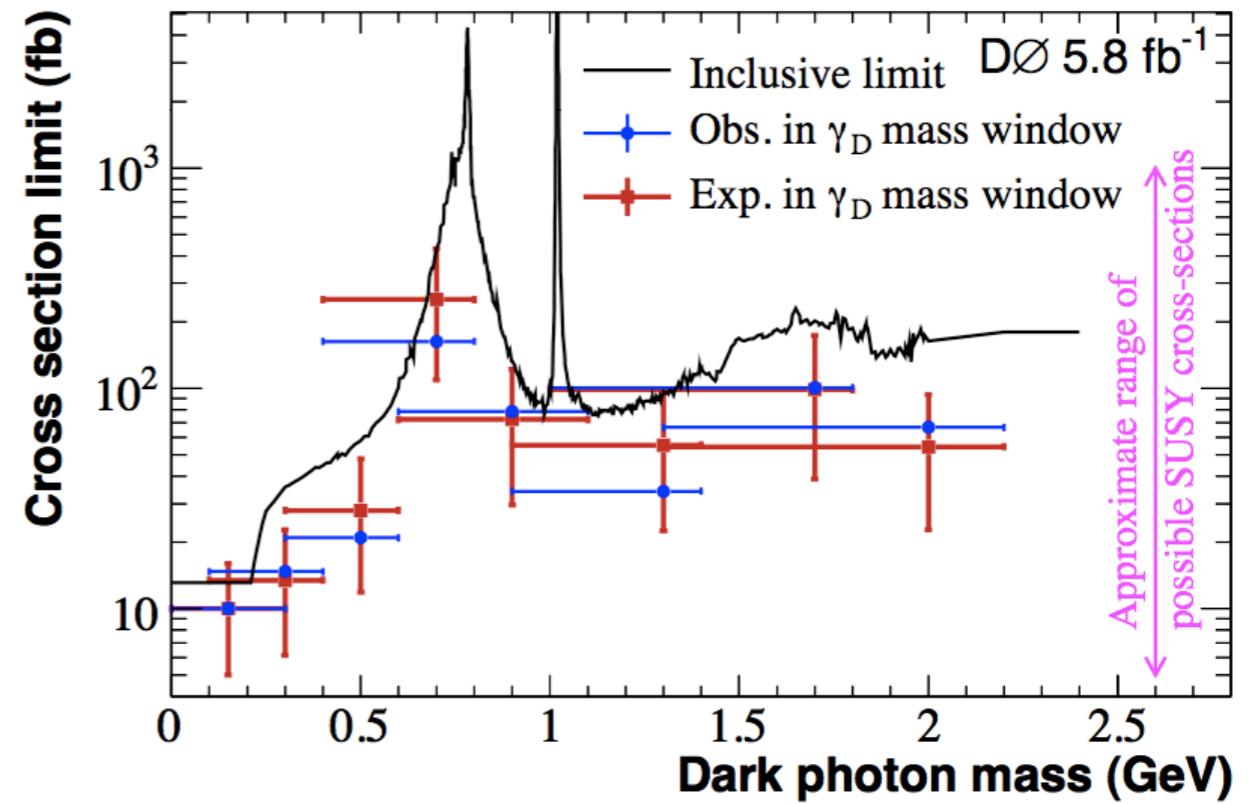
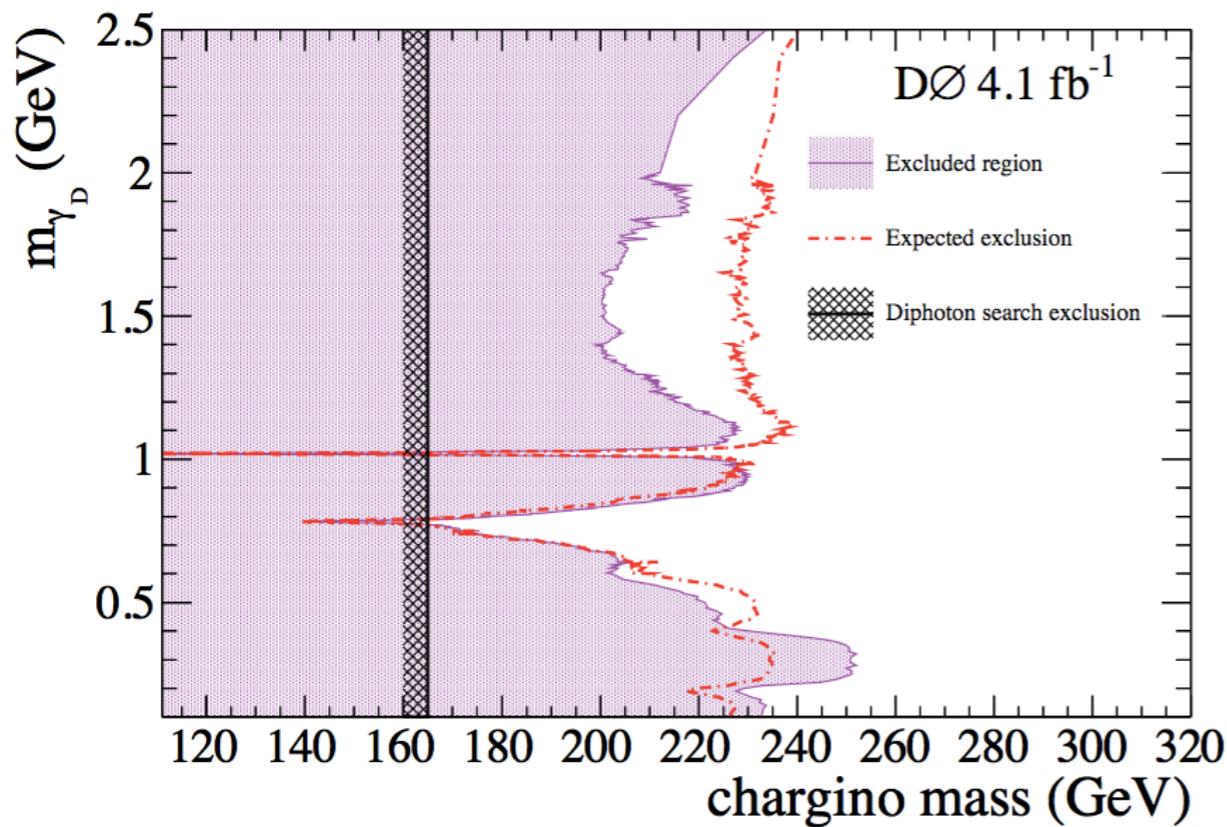
# $A'$ lifetime varies by orders of magnitude



LHC/Tevatron  
could probe  
this region, if  
SUSY particles  
are light enough

# Some Tevatron Results

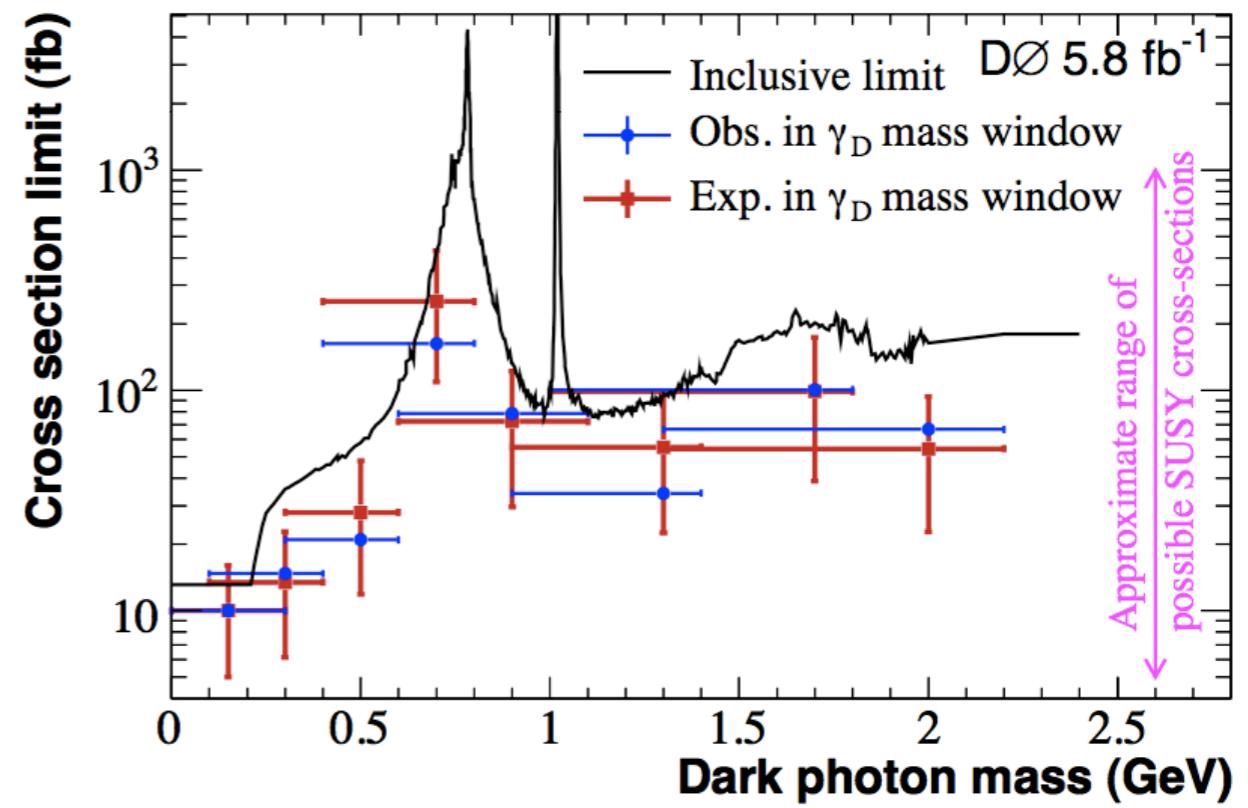
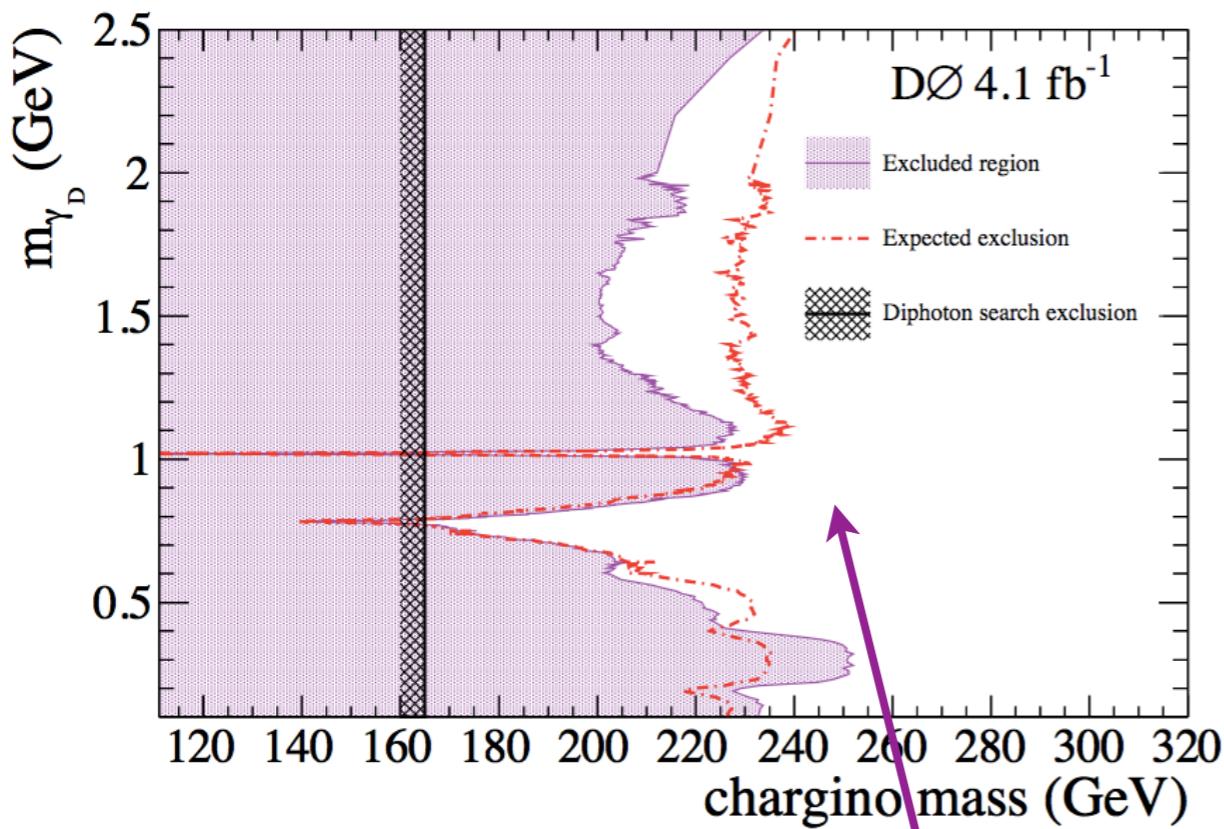
no signal yet...



arXiv:0905.1478, 1008.3356

# Some Tevatron Results

no signal yet...

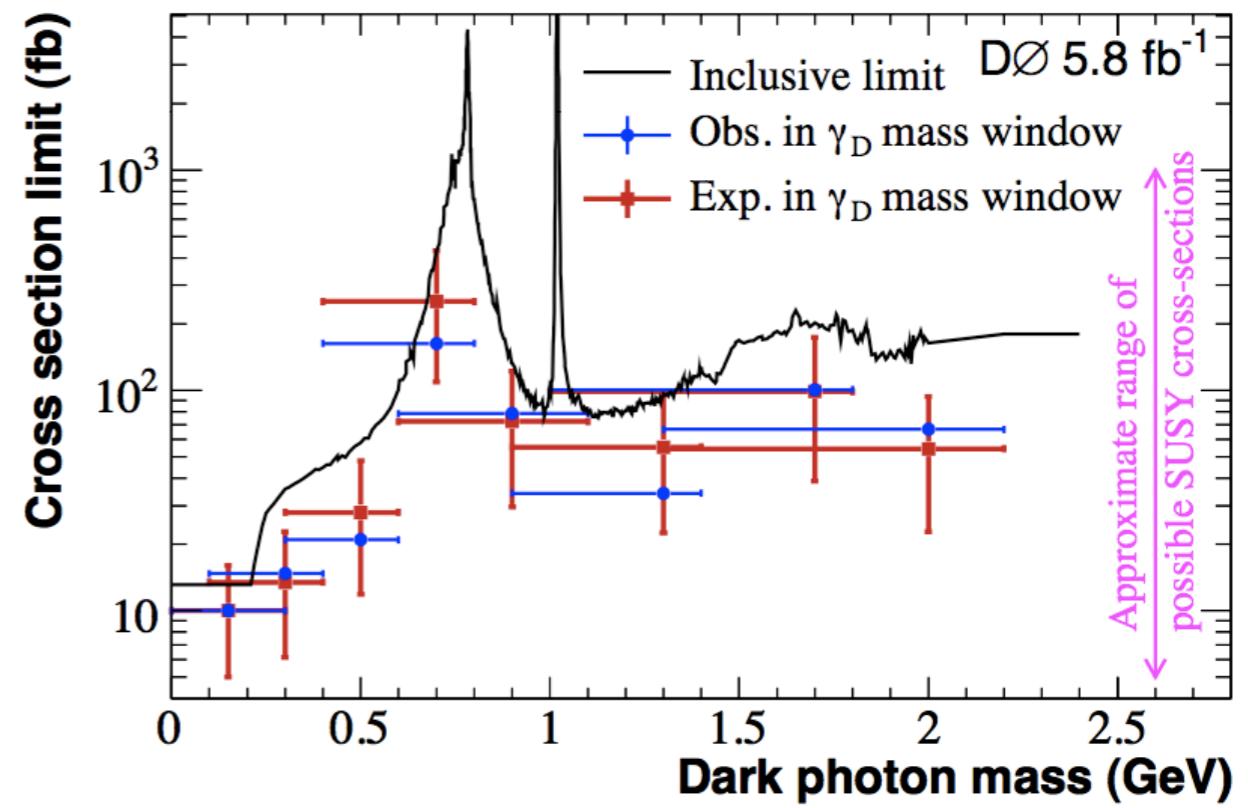
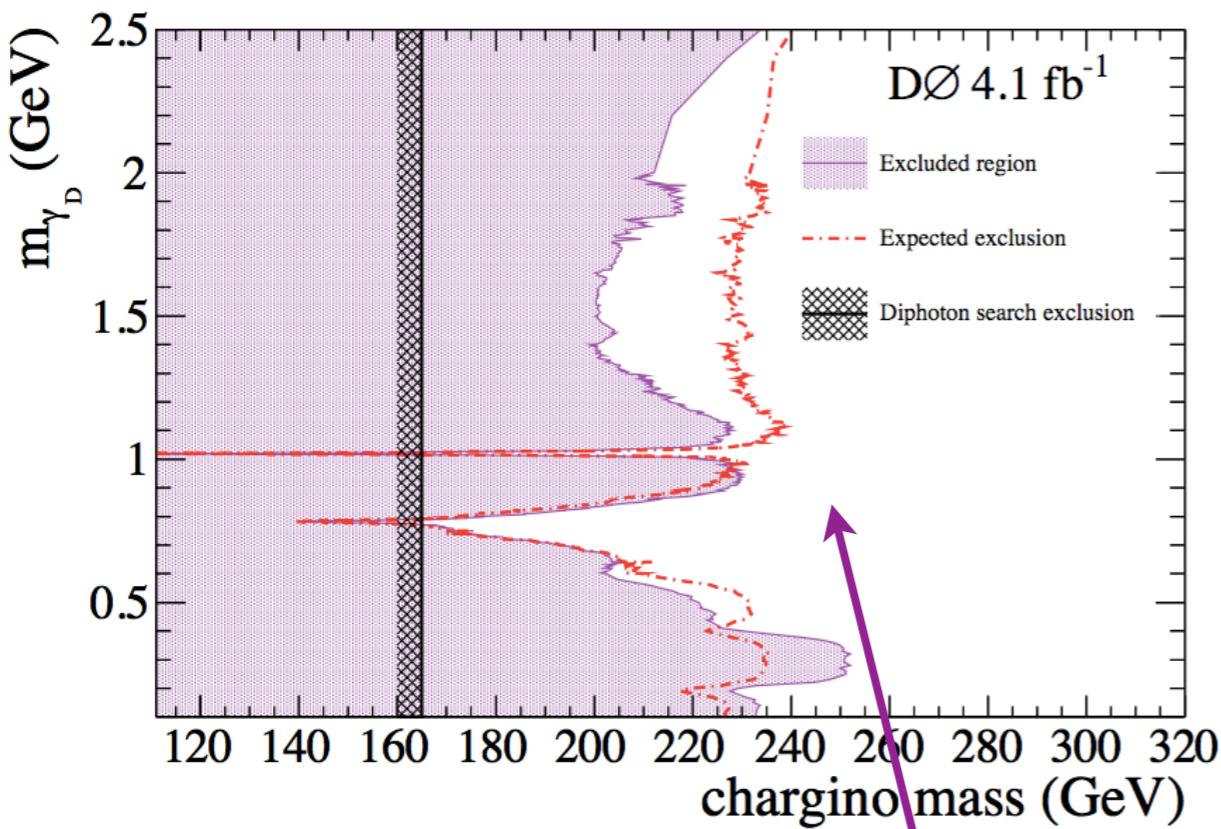


arXiv:0905.1478, 1008.3356

no limit if SUSY particles are too heavy !

# Some Tevatron Results

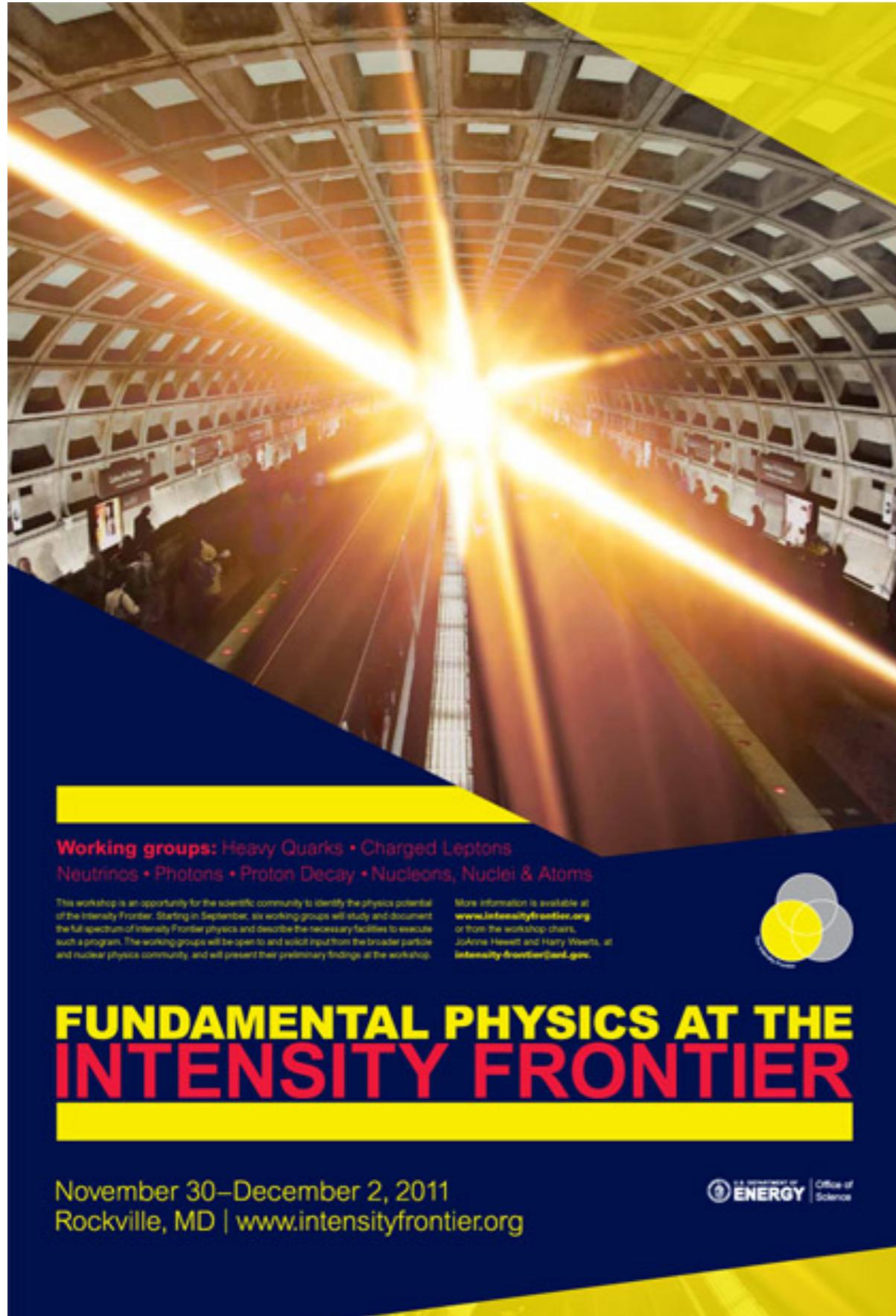
no signal yet...



arXiv:0905.1478, 1008.3356

no limit if SUSY particles are too heavy !

many LHC searches underway...



**Working groups:** Heavy Quarks • Charged Leptons  
Neutrinos • Photons • Proton Decay • Nucleons, Nuclei & Atoms

This workshop is an opportunity for the scientific community to identify the physics potential of the Intensity Frontier. Starting in September, six working groups will study and document the full spectrum of Intensity Frontier physics and describe the necessary facilities to execute such a program. The working groups will be open to and solicit input from the broader particle and nuclear physics community, and will present their preliminary findings at the workshop.

More information is available at  
[www.intensityfrontier.org](http://www.intensityfrontier.org)  
or from the workshop chairs,  
JoAnne Hewett and Harry Wietsma, at  
[intensity-frontier@ornl.gov](mailto:intensity-frontier@ornl.gov).



## FUNDAMENTAL PHYSICS AT THE INTENSITY FRONTIER

November 30–December 2, 2011  
Rockville, MD | [www.intensityfrontier.org](http://www.intensityfrontier.org)

U.S. DEPARTMENT OF  
**ENERGY** | Office of  
Science

Intensity Frontier Workshop  
requested by DoE

reviewed physics  
opportunities

A' searches (and searches for light, weakly coupled particles in general) must be part of any sensible future U.S. Intensity Frontier Program

# Conclusions

# Conclusions

- Dark photons motivated by theory, muon  $g_s$ -2, and dark matter anomalies

# Conclusions

- Dark photons motivated by theory, muon  $g_s$ -2, and dark matter anomalies
- $g_s$ -2 preferred region will be probed soon

# Conclusions

- Dark photons motivated by theory, muon  $g_s$ -2, and dark matter anomalies
- $g_s$ -2 preferred region will be probed soon
- exciting interplay between searches at intensity, energy, and cosmic frontier

# Conclusions

- Dark photons motivated by theory, muon  $g_s$ -2, and dark matter anomalies
- $g_s$ -2 preferred region will be probed soon
- exciting interplay between searches at intensity, energy, and cosmic frontier
- Worldwide effort to search for  $A'$

# Conclusions

- Dark photons motivated by theory, muon  $g_s$ -2, and dark matter anomalies
- $g_s$ -2 preferred region will be probed soon
- exciting interplay between searches at intensity, energy, and cosmic frontier
- Worldwide effort to search for  $A'$
- existing facilities have not been fully exploited - much remains to be done

# Conclusions

- Dark photons motivated by theory, muon  $g_s$ -2, and dark matter anomalies
- $g_s$ -2 preferred region will be probed soon
- exciting interplay between searches at intensity, energy, and cosmic frontier
- Worldwide effort to search for  $A'$
- existing facilities have not been fully exploited - much remains to be done
- systematic exploration for new GeV-scale forces